PB83-149583

Third Symposium on the Transfer and Utilization of Particulate Control Technology. Volume I. Control of Emissions from Coal Fired Boilers

Denver Research Inst., CO

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Jul 82

U.S. Department of Commerce
National Technical Information Service
NTIS

IERL-RTP-1318/19/20/21

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/9-82-005a	2. Proceedings	3. RECIPIENT'S ACCESSION NO. PB83 149583
4. TITLE AND SUBTITLE Third Symposium on the Transfer and Utilization of Particulate Control Technology Volume I. Control of Emissions from Coal Fired Boilers		5. REPORT DATE July 1982
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) F.P. Venditti, J.A. Armstrong, and M. Durham (Compilers)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Denver Research Institute P.O. Box 10127 Denver, Colorado 80208		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. EPA Grant R805725
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development** **Industrial Environmental Research Laboratory** **Research Triangle Park, NC 27711**		13. TYPE OF REPORT AND PERIOD COVERED Proceedings; 11/80-12/81
		14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Dale L. Harmon, Mail Drop 61, 919/541-2925. Earlier proceedings are EPA-600/9-80-039(a-d) and EPA-600/7-79-044(a-d).

16. ABSTRACT

The proceedings document the Third Symposium on the Transfer and Utilization of Particulate Control Technology, in Orlando, FL, March 9-13, 1981, sponsored by the Particulate Technology Branch of EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC. The symposium brought together researchers, manufacturers, users, government agencies, educators, and students to discuss new technology and provided an effective means for the transfer of this technology into the hands of the users. The three major categories of control technologies--electrostatic precipitators, scrubbers, and fabric filters--were the major concern of the symposium. These technologies were discussed from the perspectives of economics, new technical advancements in science and engineering, and applications. Several papers dealt with combinations of devices and technologies, leading to a concept of using a systems approach to particulate control rather than device control. Additional topic areas included novel control devices, high temperature/high pressure applications, fugitive emissions, and measurement techniques. Each of the four volumes, containing a set of related session topics, provides easy access to a unified technology area.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Fabrics	Pollution Control	13B	11E
Dust	Measurement	Stationary Sources	11G	14B
Aerosols	Processing	Particulate	07D	13H
Electrostatic Precipitation	Leakage	Fabric Filters		14G
Scrubbers		Fugitive Emissions	13I	
Dust Filters			13K	

18. DISTRIBUTION STATEMENT **Release to Public**	19. SECURITY CLASS *(This Report)* **Unclassified**	21. NO. OF PAGES 391
	20. SECURITY CLASS *(This page)* **Unclassified**	22. PRICE

EPA Form 2220-1 (9-73)

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/9-82-005a
July 1982

PB83-149583

Research and Development

EPA

Third Symposium on the Transfer and Utilization of Particulate Control Technology:

Volume I. Control of Emissions from Coal Fired Boilers

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/9-82-005a
April 1982

THIRD SYMPOSIUM ON THE TRANSFER AND UTILIZATION OF PARTICULATE CONTROL TECHNOLOGY

VOLUME I. CONTROL OF EMISSIONS FROM COAL FIRED BOILERS

Compiled by:

F.P. Venditti, J.A. Armstrong, and M. Durham

Denver Research Institute
P.O. Box 10127
Denver, Colorado 80208

Grant Number: R805725

Project Officer

Dale L. Harmon
Office of Environmental Engineering and Technology
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

Prepared for:

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

DISCLAIMER

This report has been reviewed by the Industrial Environmental Research Laboratory-Research Triangle Park, North Carolina, Office of Research and Development, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The papers in these four volumes of Proceedings were presented at the Third Symposium on the Transfer and Utilization of Particulate Control Technology held in Orlando, Florida during 9 March through 13 March 1981, sponsored by the Particulate Technology Branch of the Industrial Environmental Research Laboratory of the Environmental Protection Agency and coordinated by the Denver Research Institute of the University of Denver.

The purpose of the symposium was to bring together researchers, manufacturers, users, government agencies, educators and students to discuss new technology and to provide an effective means for the transfer of this technology out of the laboratories and into the hands of the users.

The three major categories of control technologies --electrostatic precipitators, scrubbers, and fabric filters --were the major concern of the symposium. These technologies were discussed from the perspectives of economics; new technical advancements in science and engineering; and applications. Several papers dealt with combinations of devices and technologies, leading to a concept of using a systems approach to particulate control rather than device control. Additional topic areas included novel control devices, high temperature/high pressure applications, fugitive emissions, and measurement techniques.

These proceedings are divided into four volumes, each volume containing a set of related session topics to provide easy access to a unified technology area.

VOLUME I

Page

VOLUME II. ELECTROSTATIC PRECIPITATORS--CONTENTS . . . ix
VOLUME III. PARTICULATE CONTROL DEVICES--CONTENTS . . . xiii
VOLUME IV. ATYPICAL APPLICATIONS--CONTENTS. xviii

Section A - Fabric Filters

COAL PROPERTIES AND FLY ASH FILTERABILITY. 1
R. Dennis, J.A. Dirgo and L.S. Hovis

PULSE-JET FILTRATION WITH ELECTRICALLY CHARGED FLYASH 11
R.P. Donovan, L.S. Hovis, G.H. Ramsey and J.H. Abbott

ELECTRICALLY CHARGED FLYASH EXPERIMENTS IN A LABORATORY SHAKER BAGHOUSE. 23
L.S. Hovis, J.H. Abbott, R.P. Donovan and C.A. Pareja

ELECTROSTATIC AUGMENTATION OF FABRIC FILTRATION 35
D.W. VanOsdell, G.P. Greiner, G.E.R. Lamb and L.S. Hovis

FABRIC WEAR STUDIES AT HARRINGTON STATION 45
R. Chambers, K. Ladd, S. Kunka and D. Harmon

SPS PILOT BAGHOUSE OPERATION 55
K. Ladd, W. Hooks, S. Kunka and D. Harmon

REVIEW OF SPS INVESTIGATION OF HARRINGTON STATION UNIT 2 FABRIC FILTER SYSTEM 65
K. Ladd, S. Kunka

A SUMMARY OF PERFORMANCE TESTING OF THE APITRON ELECTROSTATICALLY AUGMENTED FABRIC FILTER 75
D. Helfritch and L. Kirsten

FABRIC FILTER OPERATING EXPERIENCE FROM SEVERAL MAJOR UTILITY UNITS 82
O.F. Fortune, R.L. Miller and E.A. Samuel

EVALUATION OF THE 25 MW KRAMER STATION BAGHOUSE: TRACE ELEMENT EMISSION CONTROL. 94
M.W. McElroy and R.C. Carr

CHARACTERIZATION OF A 10 MW FABRIC FILTER PILOT PLANT 96
W.B. Smith, K.M. Cushing and R.C. Carr

VOLUME I CONTENTS (cont.)

Page

SPECIFYING A FABRIC FILTER SYSTEM 107
R.L. Ostop and D.A. Single

EVALUATION OF THE 25 MW KRAMER STATION BAGHOUSE: OPERATIONAL FACTORS IN PARTICULATE MATTER EMISSION CONTROL 118
R.C. Carr and M.W. McElroy

PULSE-JET TYPE FABRIC FILTER EXPERIENCE AT AIR TO CLOTH RATIOS OF 5 TO 1 ON A BOILER FIRING PULVERIZED COAL 120
G.L. Pearson

SELECTION AND OPERATION OF BAGHOUSES AT R.D. NIXON STATION, UNIT #1 129
R.C. Hyde, J. Arello and D.J. Huber

POTENTIAL FOR IMPROVEMENT IN BAGHOUSE DESIGN 138
R.M. Jensen

REVIEW OF OPERATING AND MAINTENANCE EXPERIENCES WITH HIGH TEMPERATURE FILTER MEDIA ON COAL-FIRED BOILERS 148
L.K. Crippen

Section B - Electrostatic Precipitators

PILOT DEMONSTRATION OF THE PRECHARGER-COLLECTOR SYSTEM. 157
P. Vann Bush, Duane H. Pontius

REMEDIAL TREATMENTS FOR DETERIORATED HOT SIDE PRECIPITATOR PERFORMANCE 165
R.E. Bickelhaupt

EVALUATION OF THE UNITED McGILL ELECTROSTATIC PRECIPITATOR 176
D.S. Ensor, P.A. Lawless, A.S. Damle

PREDICTING THE EFFECT OF PROPRIETARY CONDITIONING AGENTS ON FLY ASH RESISTIVITY. 185
R.J. Jaworowski and J.J. Lavin

SO_3 CONDITIONING TO ENABLE ELECTROSTATIC PRECIPITATORS TO MEET DESIGN EFFICIENCIES 197
J.J. Ferrigan, III

VOLUME I CONTENTS (cont.)

Page

ENHANCED PRECIPITATOR COLLECTION EFFICIENCIES THROUGH RESISTIVITY MODIFICATION 206
D.F. Mahoney

DEVELOPMENT OF A NEW SULFUR TYPE ASH CONDITIONING 216
R.H. Gaunt

OPERATING EXPERIENCE WITH FLUE GAS CONDITIONING SYSTEMS AT COMMONWEALTH EDISON COMPANY 226
L.L. Weyers and R.E. Cook

THE APPLICATION OF A TUBULAR WET ELECTROSTATIC PRECIPITATOR FOR FINE PARTICULATE CONTROL AND DEMISTING IN AN INTEGRATED FLY ASH AND SO_2 REMOVAL SYSTEM ON COAL-FIRED BOILERS 236
E. Bakke and H.P. Willett

FIELD EVALUATIONS OF AMMONIUM SULFATE CONDITIONING FOR IMPROVEMENT OF COLD SIDE ELECTROSTATIC PRECIPITATOR PERFORMANCE 237
E.C. Landhan, Jr., G.H. Marchant, Jr., J.P. Gooch and R.F. Altman

EVALUATION OF PERFORMANCE ENHANCEMENT OBTAINED WITH PULSE ENERGIZATION SYSTEMS ON A HOT-SIDE ELECTROSTATIC PRECIPITATOR 253
W. Piulle, L.E. Sparks, G.H. Marchant, Jr. and J.P. Gooch

A NEW MICROCOMPUTER AND STRATEGY FOR THE CONTROL OF ELECTROSTATIC PRECIPITATORS 265
K.J. McLean, T.S. Ng, Z. Herceg and Z. Rana

ASSESSMENT OF THE COMMERCIAL POTENTIAL FOR THE HIGH INTENSITY IONIZER IN THE ELECTRIC UTILITY INDUSTRY 272
J.S. Lagarias, J.R. McDonald and D.V. Giovanni

APPLICATION OF ENERGY CONSERVING PULSE ENERGIZATION FOR PRECIPITATORS--PRACTICAL AND ECONOMIC ASPECTS 291
H. H. Petersen and P. Lausen

Section C - Dry SO_2 Scrubbers

SO_2 REMOVAL BY DRY INJECTION AND SPRAY ABSORPTION TECHNIQUES 303
E.L. Parsons, Jr., V. Boscak, T.G. Brna and R.L. Ostop

DRY SCRUBBING SO_2 AND PARTICULATE CONTROL 313
N.J. Stevens, G.B. Manavizadeh, G.W. Taylor and M.J. Widico

VOLUME I CONTENTS (cont.)

Page

FIBER AND FABRIC ASPECTS FOR SO_2 DRY SCRUBBING BAGHOUSE SYSTEMS 323
L. Bergmann

TWO-STAGE DRY FLUE GAS CLEANING USING CALCIUM ALKALIS 333
D.C. Gehri, D.F. Dustin and S.J. Stachura

CONTROL OF SULFUR DIOXIDE, CHLORINE, AND TRACE ELEMENT EMISSIONS FROM COAL-FIRED BOILERS BY FABRIC FILTRATION 341
R.J. Demski, J.T. Yeh and J.I. Joubert

Section D - Scrubbers

FLYASH COLLECTION USING A VENTURI SCRUBBER--MINNESOTA POWER'S COMMERCIAL OPERATING EXPERIENCE 352
C.A. Johnson

AUTHOR INDEX 361

VOLUME II

ELECTROSTATIC PRECIPITATORS

Section A - Fundamentals

Page

MATHEMATICAL MODELING OF IONIC CONDUCTION IN FLY ASH LAYERS 1
R.B. Mosley, J.R. McDonald and L.E. Sparks

MEASUREMENTS OF ELECTRICAL PROPERTIES OF FLY ASH LAYERS 13
R.B. Mosley, P.R. Cavanaugh, J.R. McDonald and L.E. Sparks

LASER DOPPLER ANEMOMETER MEASUREMENTS OF PARTICLE VELOCITY IN A LABORATORY PRECIPITATOR 25
P.A. Lawless, A.S. Damle, A.S. Viner, E.J. Shaughnessy and L.E. Sparks

PROGRESS IN MODELING BACK CORONA 35
P.A. Lawless

A COMPUTER MODEL FOR ESP PERFORMANCE 44
P.A. Lawless, J.W. Dunn and L.E. Sparks

MEASUREMENT AND INTERPRETATION OF CURRENT DENSITY DISTRIBUTION AND CHARGE/MASS DATA 54
M. Durham, G. Rinard, D. Rugg and L.E. Sparks

THE RELATIONSHIP BETWEEN GAS STREAM TURBULENCE AND COLLECTION EFFICIENCY IN A LAB-SCALED ELECTROSTATIC PRECIPITATOR 66
B.E. Pyle, J.R. McDonald, W.B. Smith

PARTICLE DEPOSITION PROFILES AND REENTRAINMENT IN A WIRE-PLATE ELECTROSTATIC PRECIPITATOR 76
E. Arce-Medina and R.M. Felder

PARTICLE TRANSPORT IN THE EHD FIELD 87
T. Yamamoto

SURFACE REENTRAINMENT OF COLLECTED FLY ASH IN ELECTROSTATIC PRECIPITATORS 97
M. Mitchner, M.J. Fisher, D.S. Gere, R.N. Leach and S.A. Self

ELECTROMECHANICS OF PRECIPITATED ASH LAYERS 109
G.B. Moslehi and S.A. Self

VOLUME II CONTENTS (cont.)

Page

EXPERIMENTAL MEASUREMENTS OF THE EFFECT OF TURBULENT DIFFUSION ON PRECIPITATOR EFFICIENCY 120
G.L. Leonard, M. Mitchner and S.A. Self

CAN REENTRAINMENT BE EXPLAINED USING A NEW PRECIPITATOR FORMULA? 130
S. Maartmann

A LABORATORY FURNACE FOR THE PRODUCTION OF SYNTHETIC FLY ASH FROM SMALL COAL SAMPLES 141
K.M. Sullivan

COMPUTER SIMULATION OF THE WIDE PLATE SPACING EFFECT 149
E.A. Samuel

SIMULTANEOUS MEASUREMENTS OF AERODYNAMIC SIZE AND ELECTRIC CHARGE OF AEROSOL PARTICLES IN REAL TIME ON A SINGLE PARTICLE BASIS 160
M.K. Mazumder, R.G. Renninger, T.H. Chang, R.W. Raible, W.G. Hood, R.E. Ware and R.A. Sims

APPLICATION OF LASER DOPPLER INSTRUMENTATION TO PARTICLE TRANSPORT MEASUREMENTS IN AN ELECTROSTATIC PRECIPITATOR 169
M.K. Mazumder, W.T. Clark III, R.E. Ware, P.C. McLeod, W.G. Hood, J.E. Straub and S. Wanchoo

THE APPLICATION OF MEASUREMENTS OF AEROSOL CHARGE ACQUISITION BY BIPOLAR IONS TO THE PROBLEM OF BACK CORONA 179
R.A. Fjeld, R.O. Gauntt, G.J. Laughlin and A.R. McFarland

IDENTIFICATION OF BACK DISCHARGE SEVERITY 189
S. Masuda and Y. Nonogaki

Section B - Operations and Maintenance

MODELING OF ELECTROSTATIC PRECIPITATORS WITH RESPECT TO RAPPING REENTRAINMENT AND OUTLET OPACITY 199
M.G. Faulkner, W.E. Farthing, J.R. McDonald and L.E. Sparks

NEW PRECIPITATOR TECHNOLOGY FOR PARTICULATE CONTROL 208
J.R. Zarfoss

VOLUME II CONTENTS (cont.)

Page

AN APPLICATION SUMMARY OF HIGH ENERGY SONIC CLEANING APPLIED TO ELECTROSTATIC PRECIPITATORS 218
M.J. Berlant

THE IMPACT OF INTELLIGENT PRECIPITATOR CONTROLS 230
N.Z. Shilling, R.O. Reese and J.A. Fackler

AN ENERGY MANAGEMENT SYSTEM FOR ELECTROSTATIC PRECIPITATORS 242
R.R. Crynack and M.P. Downey

RELATIONSHIP BETWEEN ELECTROSTATIC PRECIPITATOR PERFORMANCE AND RECORDKEEPING PRACTICES 252
S.P. Schliesser

AN OPERATION AND MAINTENANCE PROGRAM FOR A PHOSPHATE ROCK ELECTROSTATIC PRECIPITATOR 262
D.B. Rimberg

Section C - Advanced Design

ELECTROSTATIC PRECIPITATOR PERFORMANCE WITH PULSE EXCITATION. 273
D. Rugg, M. Durham, G. Rinard and L.E. Sparks

DEVELOPMENT OF A CHARGING DEVICE FOR HIGH-RESISTIVITY DUST USING HEATED AND COOLED ELECTRODES. 283
G. Rinard, M. Durham, D. Rugg and L.E. Sparks

THE EVALUATION OF NOVEL ELECTROSTATIC PRECIPITATOR SYSTEMS USING A TRANSPORTABLE PROTOTYPE 295
G. Rinard, M. Durham, D. Rugg, J. Armstrong, L.E. Sparks and J.H. Abbott

ANALYSIS OF THE ELECTRICAL AND CHARGING CHARACTERISTICS OF A THREE ELECTRODE PRECHARGER 304
K.J. McLean

PARTICLE CHARGING IN AN ELECTROSTATIC PRECIPITATOR BY PULSE AND DC VOLTAGES. 314
L.E. Sparks, G.H. Ramsey, R.E. Valentine and J.H. Abbott

PARTICLE COLLECTION IN A TWO STAGE ELECTROSTATIC PRECIPITATOR WITH VARIOUS COLLECTOR STAGES. 326
L.E. Sparks, G.H. Ramsey, R.E. Valentine and J.H. Abbott

HIGH INTENSITY IONIZER DEVELOPMENT 334
M.H. Anderson, J.R. McDonald, J.P. Gooch and D.V. Giovanni

VOLUME II CONTENTS (cont.)

Page

DEMONSTRATION OF AIR POLLUTION SYSTEMS HIGH INTENSITY IONIZER/ELECTROSTATIC PRECIPITATOR ON AN OIL-FIRED BOILER 349
G.A. Raemhild, A. Prem and F. Weisz

PRIMARY AND SECONDARY IONIZATION IN AN ELECTRON BEAM PRECIPITATOR SYSTEM 358
W.C. Finney, L.C. Thanh, J.S. Clements and R.H. Davis

INFLUENCE ON PARTICLE CHARGING OF ELECTRICAL PARAMETERS AT DC AND PULSE VOLTAGES 370
H.J. Joergensen, J.T. Kristiansen and P. Lausen

BOXER-CHARGER MARK III AND ITS APPLICATION IN ESP'S 380
S. Masuda, H. Nakatani and A. Mizuno

THE PERFORMANCE OF AN EXPERIMENTAL PRECIPITATOR WITH AN ALL-PLATE ZONE 390
J. Dalmon

THE PHYSICS OF PULSE ENERGIZATION OF ELECTROSTATIC PRECIPITATORS 404
L. Menegozzi and P.L. Feldman

ADVANCED ELECTRODE DESIGN FOR ELECTROSTATIC PRECIPITATORS 405
S. Bernstein, K. Ushimaru and E.W. Geller

Section D - Industrial Applications

PROBLEMS IN APPLYING AN ELECTROSTATIC PRECIPITATOR TO A SALVAGE FUEL-FIRED BOILER. 415
C.R. Thompson

THE APPLICATION OF ELECTROSTATIC PRECIPITATORS TO BOILERS FIRING MULTIPLE FUELS 425
R.L. Bump

AUTHOR INDEX 435

VOLUME III

PARTICULATE CONTROL DEVICES

Section A - Scrubbers

Page

THE CALVERT SCRUBBER 1
S. Calvert, R.G. Patterson and S. Yung

FLUX FORCE/CONDENSATION SCRUBBER SYSTEM FOR COLLECTION OF FINE PARTICULATE EMISSIONS FROM AN IRON MELTING CUPOLA 10
S. Calvert and D.L. Harmon

DEMONSTRATION OF HIGH-INTENSITY-IONIZER-ENHANCED VENTURI SCRUBBER ON A MAGNESIUM RECOVERY FURNACE FUME EMISSIONS 21
A. Prem, M.T. Kearns and D.L. Harmon

A NEW ENTRY IN THE HIGH EFFICIENCY SCRUBBER FIELD 33
L.C. Hardison and F. Ekman

PERFORMANCE OF PARTICULATE SCRUBBERS AS INFLUENCED BY GAS-LIQUID CONTACTOR DESIGN AND BY DUST FLOCCULATION 43
K.T. Semrau and R.J. Lunn

INVESTIGATION OF VENTURI SCRUBBER EFFICIENCY AND PRESSURE DROP 51
R. Parker, T. Le and S. Calvert

SCRUBBER TECHNOLOGY AND THE INTERACTION OF A UNIQUE STRUCTURE AS MIST ELIMINATOR 60
G.C. Pedersen

NOVEL ANNULAR VENTURI SCRUBBER DESIGN REDUCES WASTE DISCHARGE PROBLEMS 71
H.P. Beutner

CONSIDERATION OF THE PERTINENT DESIGN AND OPERATING CHARACTERISTICS ESSENTIAL FOR OPTIMIZATION OF VENTURI SCRUBBER PERFORMANCE 80
H.S. Oglesby

APPLICATION OF SCRUBBERS FOR PARTICULATE CONTROL OF INDUSTRIAL BOILERS 90
M. Borenstein

VOLUME III CONTENTS (cont.)

Page

APPLICATION OF HIGH ENERGY VENTURI SCRUBBERS TO SEWAGE INCINERATION 102
F.X. Reardon

AN INCINERATOR SCRUBBER THAT WORKS: A CASE STUDY 111
C. Menoher

EVALUATION OF ENTRAINED LIQUOR CONTRIBUTION TO TOTAL MASS EMISSIONS DOWNSTREAM OF A WET SCRUBBER 119
W. David Balfour, L.O. Edwards and H.J. Williamson

Section B - Fabric Filters

A DUAL-BEAM BACKSCATTER BETA-PARTICLE GAUGE FOR MEASURING THE DUST CAKE THICKNESS ON OPERATING BAG FILTERS INDEPENDENT OF POSITION 128
R.P. Gardner, R.P. Donovan and L.S. Hovis

DIAGNOSING FILTER FABRIC CAPABILITIES WITH LIGHT SCATTERING AND NUCLEI DETECTING INSTRUMENTATION 140
R. Dennis, D.V. Bubenick and L.S. Hovis

ACID DEWPOINT CORROSION IN PARTICULATE CONTROL EQUIPMENT 150
T.E. Mappes, R.D. Tems and K.E. Foster

SECOND GENERATION OF EMISSIONS CONTROL SYSTEM FOR COKE OVENS 160
J.D. Patton

EFFECTS OF FLYASH SIZE DISTRIBUTION ON THE PERFORMANCE OF A FIBERGLASS FILTER 171
W.F. Frazier and W.T. Davis

FUNDAMENTAL STUDY OF A FABRIC FILTER WITH A CORONA PRECHARGER 181
K. Iinoya and Y. Mori

ECONOMIC EVALUATION FACTORS IN BID EVALUATIONS--A SENSITIVITY ANALYSIS 193
J.G. Musgrove and J.E. Shellabarger

FLY ASH RE-ENTRAINMENT IN A BAGHOUSE--WHAT DOES IT COST? 201
J.G. Musgrove

VOLUME III CONTENTS (cont.)

Page

WHY PERFORM MODEL STUDY OF FABRIC FILTER COLLECTOR? 211
W.T. Langan, N.Z. Shilling, W.A. Van Kleunen and O.F. Fortune

EXPERIENCES OF A SMALL INSULATION MANUFACTURER IN MAINTAINING COMPLIANCE WITH AIR POLLUTION CONTROL REGULATIONS 221
R.L. Hawks

ADVANCED FABRIC FILTER TECHNOLOGY FOR DIFFICULT PARTICULATE EMISSIONS 228
H.P. Beutner

DEVELOPMENT OF GUIDELINES FOR OPTIMUM BAGHOUSE FLUID DYNAMIC SYSTEM DESIGN 238
D. Eskinazi, G.B. Gilbert and R.C. Carr

THEORETICAL ASPECTS OF PRESSURE DROP REDUCTION IN A FABRIC FILTER WITH CHARGED PARTICLES 250
T. Chiang, E.A. Samuel and K.E. Wolpert

EXPERIMENTAL CORRELATION OF DUST CAKE POROSITY, AIR-TO-CLOTH RATIO AND PARTICLE-SIZE DISTRIBUTIONS 261
T. Chiang and R.L. Ostop

MODEL FOR DUST PENETRATION THROUGH A PULSE-JET FABRIC FILTER 270
D. Leith and M.J. Ellenbecker

PERFORMANCES OF DUST LOADED AIR FILTERS 280
C. Kanaoka, H. Emi and M. Ohta

ELECTROSTATICALLY ENHANCED FABRIC FILTRATION OF PARTICULATES 290
T. Ariman and S.T. McComas

A STAGGERED ARRAY MODEL OF A FIBROUS FILTER WITH ELECTRICAL ENHANCEMENT 301
F. Henry and T. Ariman

Section C - Granular Beds

AEROSOL FILTRATION BY A COCURRENT MOVING GRANULAR BED: PENETRATION THEORY 311
T.W. Kalinowski and D. Leith

FUNDAMENTAL EXPERIMENTS ON A GRANULAR BED FILTER 321
K. Iinoya and Y. Mori

VOLUME III CONTENTS (cont.)

Page

DRY DUST COLLECTION OF BLAST FURNACE EXHAUST GAS BY MOVING GRANULAR BED FILTER 332
A. Wakabayashi, T. Sugawara and S. Watanabe

Section D - Novel Devices

IRON AND STEEL AIR POLLUTION CONTROL USING MAGNETIC SEPARATION 341
D.C. Drehmel, C.E. Ball and C.H. Gooding

TECHNICAL AND ECONOMIC EVALUATION OF TWO NOVEL PARTICULATE CONTROL DEVICES 353
R.R. Boericke, J.T. Kuo and K.R. Murphy

THE ELECTROSCRUBBER^{TM} FILTER--APPLICATIONS AND PARTICULATE COLLECTION PERFORMANCE 363
D. Parquet

HIGH EFFICIENCY PARTICULATE REMOVAL WITH SINTERED METAL FILTERS 373
B.E. Kirstein, W.J. Paplawsky, D.T. Pence and T.G. Hedahl

APPLICATION OF ELECTROSTATIC TECHNIQUES TO THE REMOVAL OF DUST AND FUME FROM THE INDUSTRIAL ENVIRONMENT 382
S.A. Hoenig

THE DRY VENTURI 393
A.J. Teller and D.R.J. Roy

FIBER BED FILTER SYSTEM CONTROL OF WELDING PARTICULATES 398
J.A. Bamberger and W.K. Winegardner

THE USE OF GLASS CAPILLARY FILTERS TO CLASSIFY ACTINOLITE FIBERS 406
J.W. Gentry, T.C. Chen, S.W. Lin and P.Y. Yu

ULTRA-HIGH EFFICIENCY FILTRATION SYSTEMS (AIR RECIRCULATION) 417
R.W. Potokar

THE WET WALL ELECTROSTATIC PRECIPITATOR 428
J. Starke, J. Kautz and K-R. Hegemann

VOLUME III CONTENTS (cont.)

Page

Section E - Mechanical Collectors

TROUBLESHOOTING MULTIPLE CYCLONES ON FUEL-OIL-FIRED BOILERS 438
F. Crowson and R.L. Gibbs

COLLECTION EFFICIENCIES OF CYCLONE SEPARATORS. 449
P.W. Dietz

ELECTROSTATICALLY AUGMENTED COLLECTION IN VORTICAL FLOWS 459
P.W. Dietz

HIGH PERFORMANCE CYCLONE DEVELOPMENT 468
W.G. Giles

AUTHOR INDEX 481

VOLUME IV

ATYPICAL APPLICATIONS

Section A - Advanced Energy Applications

Page

HIGH TEMPERATURE PARTICLE COLLECTION WITH A.P.T. EPxP DRY SCRUBBER 1
S. Yung, T. Lee, R.C. Patterson, S. Calvert and D.C. Drehmel

PARTICLE COLLECTION IN CYCLONES AT HIGH TEMPERATURE AND HIGH PRESSURE 2
R. Parker, R. Jain, S. Calvert, D.C. Drehmel and J. Abbott

OPERATING RESULTS OF ELECTROSTATIC PRECIPITATORS AT HIGH TEMPERATURE AND HIGH PRESSURES 3
P.L. Feldman and K.S. Kumar

CONTROL OF PARTICULATES IN PROCESS AREA 12, SOLVENT REFINED COAL PROCESS 15
W.H. Wilks, P.D. Wilkinson and J.A. Schlosberg

NON-PLUGGING RETAINING STRUCTURE FOR GRANULAR BED FILTER FOR HTHP APPLICATION 26
A.M. Presser and J.C. Alexander

PARTICULATE EMISSIONS CONTROL FROM A COAL-FIRED OPEN-CYCLE MAGNETOHYDRODYNAMICS/STEAM POWER PLANT . . . 36
H.H. Wang and T.E. Dowdy

REAL TIME COARSE PARTICLE MASS MEASUREMENTS IN A HIGH TEMPERATURE AND PRESSURE COAL GASIFIER PROCESS TREATMENT 46
J. Wegrzyn, J. Saunders and W. Marlow

THE DESIGN, ENGINEERING, AND STARTUP OF A VENTURI SCRUBBER SYSTEM ON AN OIL SHALE OFF-GAS INCINERATOR . . . 55
P.A. Czuchra and J.S. Sterrett

FLUIDIZED-BED COMBUSTION HOT FLUE GAS CLEANUP PERSPECTIVE ON CYCLONES AND OTHER DEVICES 63
R.F. Henry and W.F. Podolski

PRESSURIZED AND NON-PRESSURIZED ACOUSTIC AGGLOMERATORS FOR HOT-GAS CLEANUP APPLICATIONS. 73
K.H. Chou and D.T. Shaw

VOLUME IV CONTENTS (cont.)

Page

ALKALIS AND THEIR CONTRIBUTIONS TO CORONA CURRENT AT HIGH TEMPERATURE AND HIGH PRESSURE 74
R.W.L. Snaddon

HOT GAS CLEANUP IN PRESSURIZED FLUIDIZED BED COMBUSTION 83
L.N. Rubow and M.G. Klett

VENTURI SCRUBBING FOR CONTROL OF PARTICULATE EMISSIONS FROM OIL SHALE RETORTING 95
G.M. Rinaldi and R.C. Thurnau

OVERVIEW OF THE DEPARTMENT OF ENERGY'S PRESSURIZED FLUIDIZED-BED COMBUSTOR CLEANUP TECHNOLOGY PROGRAM . . . 105
W.E. Moore

THE CYCLOCENTRIFUGE™--AN ADVANCED GAS/SOLIDS SEPARATOR FOR COAL CONVERSION PROCESSES. 116
P.R. Albrecht, J.T. McCabe and W. Fedarko

Section B - Fugitive Emissions

DEMONSTRATION OF THE USE OF CHARGED FOG IN CONTROLLING FUGITIVE DUST FROM LARGE-SCALE INDUSTRIAL SOURCES 125
E.T. Brookman, R.C. McCrillis and D.C. Drehmel

THE CONTROL OF FUGITIVE EMISSIONS USING WINDSCREENS . . . 135
D. Carnes and D.C. Drehmel

THE INFLUENCE OF AGGREGATE PILE SHAPE AND ORIENTATION ON PARTICULATE FUGITIVE EMISSIONS 145
D. Martin

SPRAY CHARGING AND TRAPPING SCRUBBER FOR FUGITIVE PARTICLE EMISSION CONTROL 155
S. Yung, S. Calvert and D.C. Drehmel

IMPROVED STREET SWEEPER FOR CONTROLLING URBAN INHALABLE PARTICULATE MATTER 156
S. Calvert, H. Brattin, S. Bhutra, R. Parker and D.C. Drehmel

A WIND TUNNEL FOR DUST ENTRAINMENT STUDIES. 168
A.S. Viner, M.B. Ranade, E.J. Shaughnessy, D.C. Drehmel and B.E. Daniels

VOLUME IV CONTENTS (cont.)

Page

TECHNIQUES AND EQUIPMENT FOR MEASURING INHALABLE PARTICULATE FUGITIVE EMISSIONS 179
H.J. Kolnsberg

BALLOON SAMPLING TO CHARACTERIZE PARTICLE EMISSIONS FROM FUGITIVE SOURCES. 188
J.A. Armstrong and D.C. Drehmel

AN ELECTROSTATICALLY CHARGED FOG GENERATOR FOR THE CONTROL OF INHALABLE PARTICLES 200
C.V. Mathai, L.A. Rathbun and D.C. Drehmel

RELATIVE EFFECTIVENESS OF CHEMICAL ADDITIVES AND WIND SCREENS FOR FUGITIVE DUST CONTROL. 210
D.C. Drehmel and B.E. Daniel

PARTICULATE IMPACT COMPARISON BETWEEN CONTROLLED STACK EMISSIONS FOR A 2000 MW ELECTRICAL GENERATING STATION 222
H.E. Hesketh and F.L. Cross

OPERATING EXPERIENCE AND THE TECHNIQUES IN THE CONTROL OF COAL DUST EMISSIONS FROM LARGE STORAGE PILE AT NANTICOKE TGS 232
N. Krishnamurthy, W. Whitman and Y.V. Nguyen

Section C - Opacity

MODELING SMOKE PLUME OPACITY FROM PARTICULATE CONTROL EQUIPMENT 242
D.S. Ensor, P.A. Lawless, S.J. Cowen

TETHERED BALLOON PLUME SAMPLING OF A PORTLAND CEMENT PLANT 252
J.A. Armstrong, P.A. Russell, M.N. Plooster

THE RELATIONSHIP OF FLY ASH LIGHT ABSORPTION TO SMOKE PLUME OPACITY 264
S.J. Cowen, D.S. Ensor

Section D - Measurements

A SPECIAL METHOD FOR THE ANALYSIS OF SULFURIC ACID MISTS 275
P. Urone, R.B. Mitchell, J.E. Rusnak, R.A. Lucas and J.F. Griffiths

VOLUME IV CONTENTS (cont.)

Page

A MICROCOMPUTER-BASED CASCADE-IMPACTOR DATA-REDUCTION SYSTEM 285
M. Durham, S. Tegtmeyer, K. Wasmundt and L.E. Sparks

DEVELOPMENT OF A SAMPLING TRAIN FOR STACK MEASUREMENT OF INHALABLE PARTICULATE 297
A.D. Williamson, W.B. Smith

INHALABLE PARTICULATE MATTER SAMPLING PROGRAM FOR IRON AND STEEL: AN OVERVIEW PROGRESS REPORT 306
R.C. McCrillis

DEVELOPMENT OF IP EMISSION FACTORS 317
D.L. Harmon

INHALABLE PARTICULATE EMISSION FACTOR PROGRAM PURPOSE AND DEVELOPMENT 326
F.M. Noonan and J.H. Southerland

INHALABLE PARTICULATE EMISSION FACTORS FOR BLAST FURNACE CASTHOUSES IN THE IRON AND STEEL INDUSTRY 335
P.D. Spawn, S. Piper and S. Gronberg

INHALABLE PARTICULATE EMISSIONS FROM VEHICLES TRAVELING ON PAVED ROADS 344
R. Bohn

QUALITY ASSURANCE FOR PARTICLE-SIZING MEASUREMENTS 353
C.E. Tatsch

PARTICULATE EMISSIONS CHARACTERIZATION FOR OIL-FIRED BOILERS 363
D. Mormile, S. Hersh, B.F. Piper and M. McElroy

A CONTINUOUS REAL-TIME PARTICULATE MASS MONITOR FOR STACK EMISSION APPLICATIONS 373
J.C.F. Wang, H. Patashnick and G. Rupprecht

Section E - Mobile Sources

STUDIES OF PARTICULATE REMOVAL FROM DIESEL EXHAUSTS WITH ELECTROSTATIC AND ELECTROSTATICALLY-AUGMENTED TECHNIQUES 383
J.L. DuBard, M.G. Faulkner, J.R. McDonald, D.C. Drehmel and J.H. Abbott

VOLUME IV CONTENTS (cont.)

Page

STUDIES OF PARTICULATE REMOVAL FROM DIESEL EXHAUSTS WITH MECHANICAL TECHNIQUES 395
M.G. Faulkner, J.L. DuBard, J.R. McDonald, D.C. Drehmel and J.H. Abbott

UPDATE ON STATUS OF CONNECTICUT'S CONTROL PROGRAM FOR TRANSPORTATION-RELATED PARTICULATE EMISSIONS 406
H.L. Chamberlain and J.H. Gastler

AUTHOR INDEX 413

COAL PROPERTIES AND FLY ASH FILTERABILITY

Richard Dennis

John A. Dirgo

GCA/Technology Division
213 Burlington Road
Bedford, MA 01730

Louis S. Hovis

Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

ABSTRACT

The results of a survey of U.S. coal sources, types, compositions, production, and use are described with the emphasis on coals whose combustion effluents are controllable with fabric filters. Physical and chemical properties of these coals and their mineral constituents were evaluated for potential impact on resultant fly ashes. Several characterizing criteria commonly used to delineate coal fouling and slagging properties were examined for probable impact upon fly ash size and surface properties. Consideration was also given to the method of coal combustion, operating temperatures, fusion and hardness properties of mineral constituents, and slag viscosity as possible factors in determining fly ash filtration characteristics. High alkalinity contents were examined for their potential to increase fly ash gas and moisture sorption. A major purpose of the survey was to provide a rationale for selecting representative fly ash samples for laboratory determination of the specific resistance coefficient (K_2) and the cleaning parameter (a_c).

BACKGROUND

Reliable predictions of fabric filter performance depend upon accurate determination of two important variables: K_2, the specific resistance coefficient for the dust; and a_c, the cleaning parameter.[1,2] Although many factors influence the filtration process, the variable indicating the air permeability properties of the dust layer (K_2) and the parameter defining the fraction of the surface dust layer removed by the cleaning action (a_c) play commanding roles in those filter systems cleaned by reverse flow air and/or by mechanical shaking. Because of limitations in the existing theory, direct measurements of K_2 and a_c represent the only safe way to evaluate these parameters. For this reason, GCA has performed under EPA sponsorship several filtration research programs involving both the prediction and direct measurement of K_2 and a_c: Contracts 68-02-1438, Task 5; 68-02-2607, Tasks 7 and 8; and 68-02-2607, Technical Directive 35. The objective of the on-going program (Contract No. 68-02-3151) is to augment the available K_2-a_c data base by searching for definitive relationships between parent coal properties and the filterability of the resultant fly ashes.

This paper reviews the background phase of this study involving the actual sample selection and the identification of relevant coal and fly ash properties. First, a rationale for the selection of specific coal fly ashes for laboratory evaluation was established based upon a detailed survey of U.S. coal production statistics and the projected use of these coals in energy generation processes where fabric filtration might be used for control of particulate emissions. Second, after determining what appeared to be representative statistics for fly ash sources and coal consumption, coal properties and other factors affecting the filterability of the resultant fly ashes were considered. These included the mineralogical composition of coal seam overburdens, floors, and partings; probable changes associated with the preparation of coal for combustion; and the impact of the combustion process itself upon fly ash characteristics.

PRELIMINARY SURVEY OF U.S. COAL PRODUCTION AND UTILIZATION

Coal production and use statistics given in Table 1 show the estimated tonnages of lignite, subbituminous, and bituminous coals that are mined in the six major U.S. coal regions and combusted in utility and industrial energy-generating operations. These data show that nearly 80 percent of the coal is produced in the Eastern and Midwestern U.S. whereas current Western output is only about 20 percent.[3] However, the increase in coal production to supply new, large (2,000 MW) power stations in the West is expected to change this balance. It should also be noted that the latter region is the source and the primary user of lignite coals.

Figure 1 shows the geographical distribution of major U.S. coal fields, the types of coal mined, and the locations of coal-burning industries and utilities that now use fabric filtration for particulate collection.[4] Coal delivery statistics demonstrate that most coal is burned in the region in which it is mined, and the average transportation distance of U.S. coal is only 592 km.[5] Detailed information concerning coal production and properties for various regions, districts, and seams may be found in the Keystone Coal Manual and related publications.[6,7]

The production statistics in Table 1 were used to establish a preliminary weighting for the selection of fly ash samples based upon emission potential. This weighting, however, could be modified to take into account any unusual coal and fly ash properties that might conceivably bias the original selection.

ANALYSES OF COAL AND FLY ASH PROPERTIES

Proximate Analyses and Sulfur Content

Proximate analyses, which describe the properties used to assign coal rankings, do not include those factors suspected to exert first order effects on fly ash filterability via their impacts on particle size. However, the moisture and ash content can affect significantly the magnitude of the uncontrolled emissions and, in turn, the design capacity and frequency of baghouse cleaning. It is also possible that the fuel composition with respect to moisture, ash, volatiles, and fixed carbon may have some bearing on the ultimate size of the non-coal mineral constituents (overburdens, partings, and floors) discharging from the pulverizers. Additionally, as ash content increases, less heat may transfer to the particles for a fixed energy input, thus retarding or preventing particle transformation to the fluid state.

Approximate average values for volatiles, sulfur, ash, and moisture contents for the six coal-producing regions are shown in Figure 2. Despite the broad range in coal analyses (and with allowances for variability in mining, cleaning, and assaying techniques), three general coal groups are discernable. Eastern coals represented by Regions I through III are characterized by medium to high volatile content, ~2 percent sulfur, low (6 to 8 percent) ash, and low (4 percent) moisture. Because of the high ash and moisture levels for Midwestern coals, the heating values are usually lower while the high sulfur content adds to the overall emissions control problems. In the case of Western Region VI coals, sulfur contents are consistently low, the volatile contents high, and, with the exception of lignites, the ash and moisture contents are similar to those for Midwestern coals. The fact that electrostatic precipitators may perform less effeciently with low sulfur coals suggests that the filtration option may be the better approach with many Western coals.

Mineralogy of Coal Seam Overburdens, Partings, and Floors

Certain minerals are associated with the common rock structures surrounding or separating coal seams as distinguished from the inorganic materials encapsulated in the parent vegetable matter from which the coals were formed. The relative hardness, chemical constituents, and fusion properties of such minerals are expected to affect particle size properties, chemical activity, and hygroscopicity of the fly ash. Generally, the similarities among the mineral fractions of most coals tend to outweigh the differences. Claystones, shales, sandstones, and slate represent typical constituents that appear in many combinations in U.S. coal formations.[6,7] In the case of sandstones with high quartz contents, one might expect to find larger ash particles and fewer fusion products (cenospheres) in the fly ash because of the hardness and high melting point for quartz. Conversely, if dolomitic species are the predominant sandstone component, pulverizing should produce finer particles because of increased friability. Reaction of calcined components with sulfur oxides may also produce a family of hygroscopic reaction products in the form of sulfites, sulfates, and bisulfites that may contribute to the formation of a "sticky" dust layer.

Chemical assays alone may not be sufficient to determine what effect the mineral content of the coal has upon the actual fly ash filtration characteristics. For example, it is expected that any inorganic species originating within the coal will appear in a finely subdivided form such that its capacity to react rapidly with flue gas components and to form finer particles far exceeds that of the coarser rock phase. The specific combinations of inorganic constituents may also play important roles in controlling the fusion and slag forming properties of the coal ash which, in turn, may impact strongly upon the quantity, shape, and size of the uncontrolled fly ash emissions.

Physical Properties and Characterizing Chemical Ratios for Typical U.S. Coal Ashes

The manner in which certain coal properties and various characterizing chemical ratios are postulated to affect fly ash collectability is indicated in Table 2. Although this listing was developed mainly from selected information sources on boiler slagging and fouling problems,[4,8] these data also provide useful guidelines pertaining to the structure of the coal fly ash particles and their ultimate behavior in a filter system. Exclusive of those ash properties that relate to the combustion and heat transfer aspects of the boiler operation, four factors may be identified that affect the fly ash filterability. These are ash melting or fusion temperatures, ash viscosity, the capacity to react with gases and/or to absorb moisture, and the ability to retain or lose electrical charge as a function of fly ash resistance properties.

Acid/Base Ratios--

Listings of the principal elements found in various U.S. coal ashes expressed as their percent oxide equivalent are presented in Table 3 along with their characterizing acid/base (A/B) ratios. As indicated in Table 2, very high or very low A/B ratios are usually associated with high melting point ashes. Conversely, minimal melting points with a rapid transition from the solid to the liquid phase are observed with a 50:50 mix, Figure 3. Assuming that ash fusion temperatures are roughly proportional to the softening temperatures, data presented in Table 3 appear to support the suggested correlation. Further details on mineral constituents and characterizing ratios, Table 4 and Figure 4, while indicating the variability in components from one area to another, also show that the A/B ratios for coals mined in the same regions or from seams that cross regional boundaries are generally similar. The numerical indices refer only to contiguous or geologically related seams and not to the previously defined coal Regions I through VI.

Silica/Alumina Ratio and Dolomite Percentage--

Examination of the softening temperatures given in Table 3 indicates no apparent correlation with either the silica/alumina ratio or the dolomite percentage. According to the theoretical effects proposed in Table 2, softening and melting point temperatures and slag viscosity should increase as either ratio increases. Figure 4 also reveals that as far as the silica/alumina ratio is concerned, there are no characterizing values associated with the arbitrary geographical (1 through 3) locations.

Iron Oxide (Percent of Total Oxides)--

With few exceptions, iron oxide (Fe_2O_3) concentrations expressed as percent of total oxides also showed very consistent relationships with respect to the three geographical areas cited in Table 4 and Figure 4. Additionally, Fe_2O_3 exhibited a good inverse correlation with the A/B ratio indicating that the SiO_2 and Al_2O_3 contents increased at the expense of a diminished Fe_2O_3 content. It was concluded that high Fe_2O_3 concentrations are indicative of A/B ratios close to unity. Therefore, one can infer that a lower melting point and less viscous slag will result with the potential to generate a larger population of smaller cenospheres in the fly ash. This concept is also partially supported by the softening temperature versus Fe_2O_3 data shown in Table 3.

Sulfur-Iron Balance--

The sulfur-iron balance indicates the extent to which the total sulfur content can be removed by pyrite separation in coal upgrading. A low ratio suggests that the coal sulfur is mainly organically bound and thus more likely to appear in the flue gas where it can adsorb on, or react with, the alkaline constituents of the ash. Conversion to soluble sulfur compounds such as alkali metal sulfites, bisulfites, and sulfates that are subsequently collected on a filter may contribute to potential plugging unless baghouse temperatures are maintained well above the dewpoint. At high total sulfur contents, a smaller fraction of iron should appear in the pyrite form. Furthermore, it has been suggested that a reduction in the pyrite content might indicate more iron in the lower oxidation state,[11] a condition observed to improve ash fluxing properties and to decrease fusion temperatures. Total sulfur contents of several Alabama coals[6] were examined as potential melting property indicators. When ash softening temperatures were plotted against total sulfur content, the random point scatter failed to support any positive correlation between the two variables or between fluxing effects and the implied iron valence state.

Total Ash Content--

The effect of ash content upon ash fusion properties was examined to determine if an increase in coal ash content might conceivably result in less heat transfer to individual mineral particles because of the dilution factor (less heat per particle). Such a process might be expected to produce generally coarser and more irregularly shaped fly ash particles. Although analyses of field data indicated a possible correlation between ash content and softening points, the relationship was too weak statistically to be of predictive value. Regardless of any possible impact upon particle size parameters or softening temperatures, filtration demands (cloth and fan capacity) will automatically relate to the volume of fly ash produced which, in turn, should relate directly to the amount of mineral present in the parent coal.

Coal Firing Method Versus Fly Ash Properties

The method of coal firing is expected to influence fly ash size properties in two ways. The degree of size reduction prior to firing determines the parent size of the fly ash constituents of the coal; i.e., that fraction of the inorganic solids contributed by the coal seam overburden, parting, or floor minerals. In the case of pulverized coal-fired boilers, the typical aerosolized material is described as 70 percent by weight less than 200 mesh (~ 74 μm). Cyclone-fired boilers ordinarily use a coarser grind, 4-14 mesh, whereas stoker coals are only crushed sufficiently to permit uniform grate loadings by the feeding mechanism.

If the size reduction process alone were the controlling factor, the ash from a pulverized coal firing system should be the finest followed by the cyclone boiler and stoker-fired products, respectively. However, the added inertial separation feature of a cyclone boiler produces a fly ash effluent even finer than that generated by pulverized coal firing. It should be noted that the potential for producing high NO_x concentrations makes doubtful the large-scale growth of this combustion system. In the case of stoker-fired boilers, the fly ash in the uncontrolled effluent is not only the coarsest but also likely to contain more unburned coal than the other effluents. As expected, the use of fly ash re-injection with spreader stokers results in a somewhat finer ash. At this time, the relationships between fly ash size and firing method are restricted to qualitative applications because of measuring problems, variations in system geometries and particulate residence times in the systems, and settlement factors (bottom versus fly ash). Nevertheless, it is important that the firing method be considered along with other factors suspected to affect the ultimate filterability of coal fly ash.

SUMMARY AND CONCLUSIONS

An investigation of coal production and utilization statistics in conjuncton with the identification of coal properties, treatment, and combustion procedures that might affect fly ash filterability was performed to establish a basis for selecting representative fly ash samples for detailed study. A determination of key filtration parameters, K_2 and a_c, describing filter resistance and fabric cleanability, respectively, is now underway to permit broader applications of the EPA filtration model.[2] Analyses of the data base developed for this study provided the rationale for the conclusions on fly ash selection listed below:

1. The number of fly ash samples to be investigated for any coal type should reflect the best projections for current and future use of that coal in applications where fabric filters can provide the particulate emission control. For example, Region VI coals have been given an increased weighting because of projections for much increased future usage and the unusually high ash contents of some lignite coals.

2. Basic coal properties, as delineated by proximate analyses, are similar for Regions I, II, and III. Thus, fly ash samples obtained from cooperating utilities and industries that burn coal from these regions can be treated as a single class. The approximate number of samples will be based on the combined regional output used for power, steam, and heat generating purposes.

3. The distribution of fly ash samples should be representative of the principal coal firing methods. Although pulverized coal firing is far more common on the basis of fuel consumption, there are fewer and sometimes more conflicting data available on the properties of uncontrolled fly ash emissions from stoker-fired boilers. Therefore, increased sampling above that suggested by the fuel use criterion is required for stoker-fired systems.

4. The physical properties of the mineral constituents of a coal considered most likely to affect fly ash properties are hardness and melting (and softening) point. Both may affect fly ash size properties, the latter through its impact on slag viscosity. Of the several characterizing ratios for mineral constituents claimed to affect slag viscosity, the acid/base ratio alone appears to have a predictive value. Thus, when more than one sample is selected from any region, at least two A/B levels should be tested.

5. High calcinable mineral and/or sulfur contents contribute to increased fly ash hygroscopicity, which may present difficulties when baghouse temperatures are allowed to fall below the dewpoint. Excess moisture condensation causes reduced dust cake porosity that leads to prohibitively high filter pressure loss. On the other hand, although low sulfur coals present few condensation problems, an excess electrical charge accumulation may interfere with normal filtration processes. Therefore, the fly ash sampling should include both low and high sulfur coals.

ACKNOWLEDGMENTS

This project has been funded at least in part with Federal funds from the U.S. Environmental Protection Agency under Contract 68-02-3151. This paper does not necessarily reflect the views or policies of the U.S. Environmental Protection Agency, nor does mention of trade names, commercial products, or organizations imply endorsement by the U.S. Government.

REFERENCES

1. Dennis, R. and J.A. Dirgo. Comparison of Laboratory and Field Derived K_2 Values for Dust Collected on Fabric Filters. Proceedings, U.S.-Japan Scientific Seminar, Measurement and Control of Particulates Generated from Human Activities. Kyoto, Japan. November 10-14, 1980.

2. Dennis, R. and H.A. Klemm. A Model for Coal Fly Ash Filtration. J. Air Pollut. Control Assoc. 29:230-234 (1979).

3. Energy Data Report. Coal-Bituminous and Lignite in 1976. DOE/EIA-0118/1 (1976). Prepared in the Office of Energy Data and Interpretation, U.S. Department of Energy. December 18, 1978.

4. Gibbs and Hill, Inc. Coal Preparation for Combustion and Conversion. Prepared for Electric Power Research Institute. EPRI AF-791, Project 466-1, Final Report. May 1978.

5. The Direct Use of Coal: Prospects and Problems of Production and Combustion. Prepared by the Office of Technology Assessment, Congress of the United States. OTA-E-86. April 1979.

6. Nielson, G.F. (Editor-in-Chief). 1979 Keystone Coal Industry Manual. McGraw-Hill, Inc. New York, New York. 1979.

7. Nielson, G.F. (Editor-in-Chief). U.S. Coal Mine Production by Seam - 1976. McGraw-Hill, Inc. New York, New York. 1977.

8. Winegartner, E.C. (Editor). Coal Fouling and Slagging Parameters, Report by ASME Research Committee on Corrosion and Deposits from Combustion Gases, ASME (1974).

9. White, H.J. Electrostatic Precipitation Research, Precipitator Design. J. Air Pollut. Control Assoc. 27:206-217 (1977).

10. Perry, R.H., C.H. Chilton, and S.D. Kirkpatrick (Editors). Chemical Engineer's Handbook, 4th Ed. Section 9, Table 9-2. McGraw-Hill, Inc. New York, New York. 1969.

11. Plumley, A.L. Fossil Fuel and the Environment, Present Systems and Their Emissions. Combustion Engineering, Inc. October 1971.

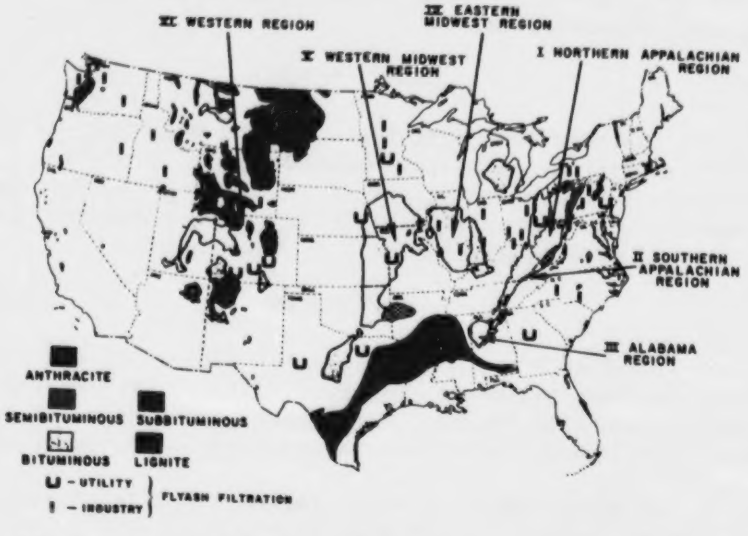

VI WESTERN REGION
IV EASTERN MIDWEST REGION
V WESTERN MIDWEST REGION
I NORTHERN APPALACHIAN REGION
II SOUTHERN APPALACHIAN REGION
III ALABAMA REGION
ANTHRACITE
SEMIBITUMINOUS
SUBBITUMINOUS
BITUMINOUS
LIGNITE
U - UTILITY
I - INDUSTRY
FLYASH FILTRATION

Figure 1. Coal Fields of The United States and Sites Selected to Obtain Fly Ash.[4]

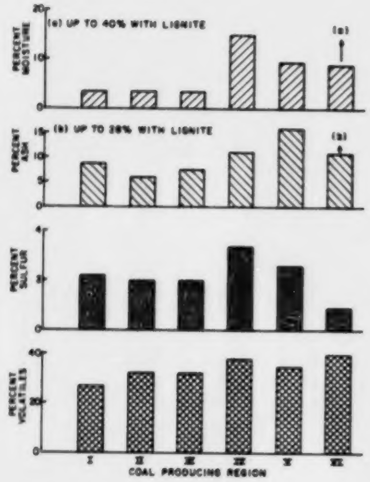


Figure 2. Averaged coal analyses for major coal Regions.

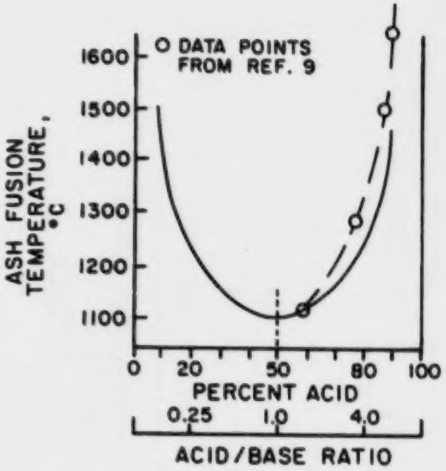


Figure 3. Effect of acid/base ratio on ash fusion temperature.[4]

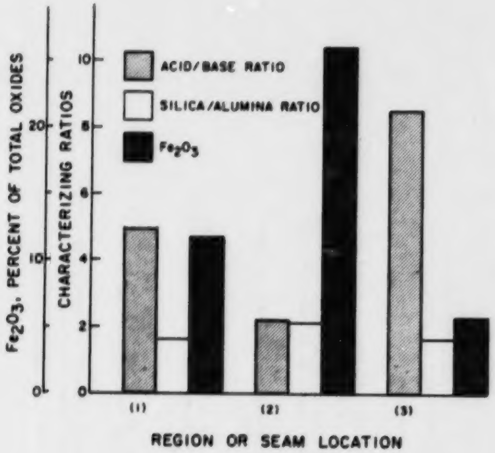


Figure 4. Characterizing ratios versus location of coal seam. Refer to Table 4.

TABLE 1. ESTIMATED COAL PRODUCTION USED BY UTILITIES AND INDUSTRY FOR ELECTRICAL POWER, STEAM, OR HEATING PURPOSES

Region	States	Production 10^6 metric tons/year
I Northern Appalachian	PA,WV(n)*,OH,MD,MI	128 (26.2)†
II Southern Appalachian	WV(s),VA,KY(e),TN(n)	110 (22.5)
III Alabama	AL,GA,TN(s)	13 (2.6)
IV Eastern Midwest	KY(w),IN,IL	120 (24.6)
V Western Midwest	AR,IA,OK,KS,MO,TX	23 (4.6)
VI Western	CO,WY,MT,SD,ND,UT, NM,AZ,ID,WA,AK	95 (19.5)

*Letters in parentheses refer to north, south, east, and west.

†Numbers in parentheses refer to percent of total.

TABLE 2. CHARACTERIZING COAL PROPERTIES AND PARAMETERS THAT MAY AFFECT FLY ASH FILTERABILITY

Property or parameter	Probable effect on fly ash and its filterability
1. Ash Fusion Temperature	More cenospheres, finer particles, and higher K_2 at low fusion temperature. More and larger irregular particles at high fusion temperature and easier cleaning.
2. Hardness (Grindability)	Larger particles, fewer cenospheres, and lower K_2 with harder minerals.
3. Silica/Alumina Ratio	Lower ratio decreases viscosity and particle size with higher K_2, more difficult cleaning.
4. Acid/Base Ratio (A/B) $\frac{SiO_2, Al_2O_3, TiO_2}{Fe_2O_3, CaO, MgO, K_2O, Na_2O}$	Lower melting point and viscosity as A/B ratio approaches unity; finer particles with higher K_2 and more difficult cleaning.
5. Dolomite Percentage (D.P.) $100x \frac{CaO, MgO}{Fe_2O_3, CaO, MgO, K_2O, Na_2O}$	Slag viscosity and size increase with dolomite percentage; lower K_2 and easier cleaning.
6. Sulfur-Iron Balance $\frac{\text{Total } Fe_2O_3 \text{ in ash}}{Fe_2O_3 \text{ equivalent of 50 percent of sulfur as } FeS_2}$	High sulfur to iron balance increases fly ash acidity and hygroscopicity; fabric plugging and chemical attack, minimal electrical charge effects.
7. Total Alkali Content (T.A.) $(Na_2O + K_2O) \times (Ash)$	High alkali content increases fly ash hygroscopicity and stickiness (increased electrical conduction may improve ESP performance)
8. Water Soluble Content Na and K content by boiling and reflux in water.	Increased solubles (usually Na and K) increase fly ash hygroscopicity and stickiness, reduced electrical resistivity.

Items 1,3-5[8]; Item 2[9]; Items 6-8[4]

TABLE 3. SOFTENING TEMPERATURES, ASH CONSTITUENTS AND CHARACTERIZING RATIOS FOR SEVERAL U.S. COALS[10]

Coal Source	Softening temperature °C	Coal ash analysis, percent								Acid/ Base ratio	Silica/ Alumina ratio	Dolomite percentage
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O K_2O	SO_3			
Montana Subbituminous	1130	30.7	19.6	18.9	1.1	11.3	3.7	2.4	12.2	1.42	1.57	41
Illinois Bituminous	1270	46.2	22.9	7.7	1.0	10.1	1.6	1.5	8.9	3.35	2.02	56
Pennsylvania Bituminous	1370	49.7	26.8	11.4	1.2	4.2	0.8	2.9	2.5	4.03	1.85	26
West Virginia Bituminous	1500	51.0	30.9	10.7	1.9	2.1	0.9	1.4	0.6	5.55	1.65	20
Kentucky Bituminous	>1595	58.5	30.6	4.2	1.8	2.0	0.4	1.6	0.9	11.1	1.91	29

TABLE 4. CHEMICAL CONSTITUENTS OF TYPICAL COAL ASHES EXPRESSED AS PERCENT OF TOTAL OXIDES[4]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Acid/base* ratio	Silica/ alumina ratio
Alabama,										
Tuscaloosa County	48.2	28.4	15.1	1.8	0.8	0.3	1.2	2.4	4.34 (1)	1.7
Illinois,										
Stark County	42.1	20.1	22.8	6.6	1.1	0.5	1.9	2.0	1.95 (2)	2.09
Schuyler County	48.0	14.7	18.7	10.4	0.6	0.2	1.8	2.1	2.04 (2)	3.26
Kentucky,										
Pike County	52.0	34.5	6.4	1.9	0.6	0.5	3.3	0.8	6.85 (1)	1.51
Bell County	46.9	28.4	12.0	2.7	2.0	0.2	2.0	4.5	4.54 (1)	1.66
Ohio County	49.3	19.4	27.4	1.8	0.7	0.2	1.9	0.2	2.22 (2)	2.54
Ohio,										
Belmont County	42.4	19.6	27.5	4.8	1.2	0.2	1.6	2.0	1.81 (2)	2.16
Jefferson County	50.4	23.2	21.9	1.9	0.5	0.1	1.0	0.4	2.90 (2)	2.17
Noble County	36.7	19.9	37.8	1.8	0.6	0.2	1.4	0.7	2.08 (2)	1.84
Pennsylvania,										
Bedford County	57.7	32.1	5.1	1.7	0.9	0.2	2.6	0.2	8.57 (3)	1.80
Allegheny County	49.2	24.8	20.3	1.8	0.5	0.2	3.6	1.3	2.84 (2)	1.98
Butler County	26.9	18.2	52.5	1.2	0.4	0.2	1.0	0.8	0.83 (2)	1.48
West Virginia,										
Barbour County	52.5	35.6	6.1	1.8	0.6	0.2	1.9	0.9	8.39 (3)	1.47
Fayette County	48.5	30.1	13.6	1.8	0.8	0.7	2.6	1.3	4.02 (1)	1.61
Kanawha County	37.9	23.8	31.4	2.0	0.5	0.5	0.5	2.9	1.85 (2)	1.60

*Numbers in parentheses designate arbitarary geographical locations for coal seams expected to display similar mineral assays.

PULSE-JET FILTRATION WITH ELECTRICALLY CHARGED FLYASH

By: R.P. Donovan
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, N.C. 27709

L.S. Hovis, G.H. Ramsey, J.H. Abbott
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

ABSTRACT

Pulse-jet performance equations differ from those of reverse-air-cleaned or shaker-cleaned baghouses, especially when operated at high air-to-cloth ratios as has been described by Leith, Ellenbecker, Dennis, and others. These differing performance equations imply that dust electrical charge should influence pulse-jet performance differently than, say, shaker-baghouse performance. Measurement protocol distinguishing between conventional pulse-jet operation and a "dust cake" mode of pulse-jet operation is described and the initial results of an experimental program derived from this distinction are presented. Comparisons with the shaker baghouse are emphasized.

TEXT

Electrical charge as a means of enhancing fabric filtration performance is receiving a "big play" in the contemporary fabric filtration literature (Cooper, 1979; Ariman and Helfritch, 1980). Previously reported EPA in-house research with actively charged flyash systems has been carried out with the shaker baghouse (Hovis, *et al.*, 1981; Donovan, *et al.*, 1981). This paper describes complementary work initiated in the EPA pulse-jet baghouse in which flyashes similar to those tested in the shaker baghoue are used in various operating modes of the pulse jet. The capability of experimenting with similar flyashes, either uncharged or charged, provides insights into the mechanisms of the two types of filtration equipment and also helps to isolate charge effects and charge-affected mechanisms of filtration.

This paper begins by reviewing important differences between pulse-jet fabric filtration and shaker-cleaned fabric filtration. Models of charge-enhanced fabric filtration often attribute the enhancement to a charge-induced increase in dust-cake porosity (Cooper, 1979). Because of significant differences between the dust cake on a shaker-cleaned woven fabric and the dust layer on a pulse-jet-cleaned felt fabric, such dust-cake porosity models immediately alert one to anticipate that a different charge interaction could dominate each of these two common techniques of fabric filtration.

Much of the work to be presented here was undertaken in an attempt to distinguish between these two operating modes and the effect of dust electrical charge on each; particular emphasis is placed on operating the pulse-jet equipment in the "dust cake" mode. This experimental, non-practical mode of pulse-jet operation simulates the shaker cycle in that it features long filtration periods (9-120 minutes), followed by a multi-pulsed (40 pulses), off-line cleaning prior to the next filtration cycle. The reason for such non-standard operation is to be able to form a dust cake in the pulse jet and to produce a dust-cake-layer-dominated ΔP characteristic by which performance can be measured, and from which charge dependence of the performance can be detected.

In the description of the pulse-jet apparatus, emphasis is placed on those equipment properties that are expected to influence charged-dust filtration differently than in the shaker baghouse. The Results section also includes shaker-baghouse results with which various performance comparisons are made.

Background

Conventional pulse-jet operation refers to fabric filtration which features, in addition to bag cleaning by a short (typically 50-150 ms) burst of compressed air fired down the bag through a venturi nozzle: outside collection, on-line cleaning, higher superficial gas flows than shaker or reverse-air cleaned units, and shorter intervals between cleaning cycles than the typical shaker or reverse-air unit. Departures from one or more of these properties are commonplace; however, not all pulse jets use venturis (some don't even use an aimed blow pipe above the bags but resort to a more remote pulse-control mechanism as in the plenum-pulse design), not all pulse jets are outside collectors (some are cageless with strictly induced pulse cleaning initiated at the bag bottom), and more and more pulse jet operators are resorting to off-line cleaning. In short, the term pulse jet no longer adequately defines a specific standardized fabric filtration operation--if it ever did. The key properties of what is defined in this paper as "conventional" pulse-jet operation are:

1. a residual dust load in/on the fabric that is large with respect to the fresh dust fed between successive cleaning pulses;
2. a low cleaning efficiency in the sense that only a small percentage of the dust load on the fabric is transferred to the hopper in any single cleaning cycle; and
3. significant dust redeposition after a cleaning pulse because of the on-line cleaning.

These properties of the "conventional" mode of operating a pulse jet follow from the process descriptions of Dennis and Klemm (1980), Ellenbecker and Leith (1979, 1980), Leith and First (1977), Leith and Ellenbecker (1980), and Leith, et al., (1980). These publications emphasize the differences between pulse-jet fabric-filter performance equations and the ideal Darcy equations which have been used to predict shaker or reverse-air baghouse performance by modeling filtration as a dust-cake dominated process.

Particular attention is drawn to the presence of the larger quantity of dust that remains on the bag during conventional pulse-jet filtration when compared to dust-cake filtration processes. This retained dust is not necessarily all residual dust that is never removed from the bag, but may consist of cleaned dust that has redeposited on the bags rather than fall to the hopper. Regardless, its presence adversely affects conventional pulse-jet performance and limits the range of practical operating gas-to-cloth ratios.

That the performance of a conventional pulse jet depends so strongly on retained dust implies that understanding the effect of dust electrical charge in a conventional pulse jet will require knowledge of not only the incoming dust charge but also that of the retained dust layer. In addition the influence of dust charge upon the various interactions (such as initial capture, cleaning efficiency, and redeposition) must be known. From these considerations the conventional pulse-jet problem is expected to be more complicated than dust-cake filtration in, say, the shaker baghouse.

For these reasons a preliminary experimental program has been defined prior to addressing the conventional pulse-jet problem. In this initial phase of the EPA/IERL-RTP in-house program, the pulse-jet equipment is operated in a "dust-cake" mode which implies the following modifications:

1. filtration periods sufficiently long to build a dust cake on the fabric, analogous to that in a shaker operation; and
2. off-line cleaning in which multiple pulses are fired through all bags simultaneously and in sufficient number to reduce the residual dust areal density to 250-300 g/m^2.

The fabrics and superficial velocities of filtration used, however, are those typical of conventional pulse-jet filtration. The goal is to understand the dust collection process and the influence of dust charge upon it before considering the effects of dust charge upon the dominating effects of conventional pulse-jet cleaning. In addition the pulse-jet equipment lends itself to crude bag weighing and thus enables direct measurements of total dust gain by the bags during a given filtration cycle. This information is particularly valuable in separating charge-related dust-cake porosity effects from precharger dust collection effects, a difficult separation to make with the shaker baghouse (Hovis, et al., 1981).

Apparatus

The in-house laboratory pulse-jet baghouse is a commercially available, nine-bag Mikro-Pul baghouse operated as previously described by Turner (1977). It consists of three rows of three bags each. Each bag is mounted on the shoulder of a venturi nozzle which itself is sealed to a tube sheet. A blow pipe is positioned above each row with an orifice opposite the bag mouth. Cleaning pulses were drawn from a 90-psi (620 kPa) reservoir of compressed air for all data to be reported.

Dirty air enters the hopper beneath the bags and flows through the bags outside-in. The bags are mounted on steel cages to prevent collapse during filtration.

To this standard apparatus various additions have been made as shown in Figure 1. A prime addition is that of the corona precharger shown in the inlet duct. This precharger consists of a single wire mounted along the centerline of the inlet duct. The corona discharge by which the incoming dust is charged occurs along the 1/16-inch (1.6 mm) welding rod shown protruding from the larger diameter mount. The larger diameter mount is held in position by two Teflon standoffs which extend across the diameter of the duct and through which the high voltage is routed to the wire.

This location of a precharger suffers from two shortcomings:

1. the remoteness of its location from the bags; and
2. the high speed of the gas flow through the precharger and hence the short charging time available for charging the dust.

Simple calculations suggest that, in spite of the short residence time in the corona region, significant dust charging can occur with this precharger design (Appendix 1). Charge loss between the precharger and the bags proved difficult to sample and measure accurately so a second precharger design (Figure 2) was built to mount immediately beneath the bags in a region that is both nearer the bags and in a region of lower linear gas flow than the duct precharger. Most of the dust-cake mode data were taken with this second precharger design, called the plenum precharger.

The plenum precharger design, however, does not match up well with the study of conventional pulse-jet service because it is located between the dust on the bags and the hopper. Dust removed from the bag by the pulse-jet cleaning action then must pass through the precharger to reach the hopper and hence is subject to capture by the precharger. Even some dust that normally would be redeposited could be captured by the precharger electric field because of its location. Hence, this precharger location complicates data interpretation.

The duct charger, on the other hand, is out of the dust path between the bags and the hopper and, in addition, operates with little dust capture in the duct itself, although wall capture by the hopper and lower baghoue chamber will still be enhanced when the precharger is ON. Stable precharger operation is easier to achieve with this arrangement, however.

Other ports have also been added to the baghouse as illustrated in Figure 1. Two ports for inserting an impactor into the baghouse chamber now exist. This in-the-housing capability minimizes probe losses during impactor sampling.

The test dusts used in the pulse-jet experiments are the same Southwestern Public Service (SPS) flyash and Detroit Edison flyash (DEF) used in the shaker-baghouse experiments (Hovis, et al., 1981). While the inlet dust concentration in the pulse jet is generally higher than in the shaker baghouse (4 gr/ft^3 [9 g/m^3] vs 3 gr/ft^3 [7 g/m^3]), the hopper fallout characteristic of this particular pulse-jet operation (~ 50%) reduces the dust concentration reaching the bags to about 2 gr/ft^3 (4.5 g/m^3). Hopper fallout in the top fed shaker unit is essentially zero.

Most of the data to be reported in the pulse jet were taken at an operating air-to-cloth ratio of 9 ft/min (4.5 cm/sec). This value is more than double the 4 ft/min (2 cm/sec) superficial velocity at which the shaker operates. Relative humidity in both baghouses is controlled by the same Inreco®

controller--the same feedhouse that encloses the pulse-jet hopper also encloses the shaker-baghouse hopper.

The only fabric used in the pulse-jet tests to be reported is a needled polyester felt weighing 16 oz/yd^2. These bags were purchased from Mikro Pul.

This fabric style is the second major difference (next to cleaning technique) between the pulse-jet experiments and the shaker experiments.

Results

Most of the evaluations of charged dust effects in pulse-jet fabric filtration carried out in the EPA pulse jet have been made in the dust-cake mode prevously described. This mode allows a separation of charge effects on fresh incoming dust from those on the retained or redeposited dust. In the dust-cake mode, only off-line cleaning is carried out; the only evaluating measurements, in addition to the usual pressure drop and flow-rate records, are total bag weight before and after the cleaning. The measurement procedure, beginning with cleaned bags, thus is:

1. Remove bags from baghouse and weigh, one at a time. Reinstall bags in identical slots from which removed.
2. Run under desired test conditions.
3. At end of run, slip a plastic cover over each bag; remove and weigh each bag.
4. Reinstall bags and clean with 40 pulses at 90 psi (620 kPa).
5. Repeat Step 1.

For these dust-cake mode measurements, only three bags were used; the other six slots of the nine-bag baghouse were capped off. The three bags were mounted on one row (Row 2) so that they were cleaned simultaneously; the cleaning control was rewired so that only this row was actuated for cleaning.

Figure 3 is a sketch of a typical pressure trace operating in the dust-cake mode. In contrast to the shaker baghouse pressure trace, all the pulse-jet pressure traces initially exhibited what Dennis and Klemm (Nov., 1980) describe as concave-up behavior; but, if allowed to continue for long periods of time and to build up large pressure drops, the traces eventually displayed linear behavior from which a specific dust-cake resistance (K_2') could be estimated. Because the length of this initial non-linear region is a significant fraction of the typical filtration period, the K_2' calculation was modified as follows:

$$K_2' = \frac{(\Delta P_F - \Delta P_{DCO})A}{m_T\left(\frac{t_2 - t_1}{t_2}\right)V} \qquad (1)$$

where ΔP_F, ΔP_{DCO}, t_1, and t_2 are defined in Figure 3;

A = total fabric area;

m_T = total weight gain of all bags during the filtration period t_2; and

V = the gas-to-cloth ratio.

The $(t_2-t_1)/t_2$ correction assumes that only that fraction of the total dust gain of the bags that occurred during the linear buildup region is appropriate for the K_2' calculation--the earlier dust deposit is at some lower effective K_2' rate and represents a dust/felt interface (or other non-dust-cake) property. The corresponding pressure drop $(\Delta P_F - \Delta P_{DCO})$ of the linear region is used in the numerator of Equation (1).

Tables 1 and 2 summarize measurements for DEF and SPS flyash, respectively. K_2' in these tables has been calculated by Equation (1), using the $(t_2-t_1)/t_2$ correction factor when a clearly defined linear region exists in the experimental pressure trace. Otherwise $(t_2-t_1)/t_2$ was set equal to 1. A major effect of turning the plenum precharger ON is to reduce the quantity of flyash reaching the bags, presumably because of precharger and wall capture. This effect repeats the observations of the shaker baghouse (Hovis, et al., 1981). The improved precharger performance with relative humidity (in the sense of enhanced flyash capture) also repeats in this pulse-jet arrangement. At 70% relative humidity the mass of flyash reaching the bags when the precharger is ON is only 20-30% of that when the precharger is OFF. At 30% relative humidity this ratio is greater.

Values of K_2' calculated by the mass corrected expression given by Equation (1) do not show a significant dependence on dust charge for either of these flyashes. As was true for the shaker results, the dramatic change in the ΔP trace upon turning ON the precharger (Figure 4) is primarily explained as flyash capture by the precharger, thus reducing the effective flyash feed rate to the bags. When this flyash loss is accounted for by direct bag weighing, the K_2' values calculated from Equation (1) are similar for the charged and the uncharged flyashes.

As with the shaker data, this conclusion does not rule out the charge-induced porosity increase reported by others (Chudleigh and Bainbridge, 1980; Ariman and Helfritch, 1980; Iinoya and Mori, 1980) so much as demonstrate that such an effect is smaller in magnitude than the precharger collection effect. The bag weighing technique employed here is still a coarse measurement that is time consuming and technique dependent. Nonetheless the precharger mass collection effect is clear, while the dependence of flyash porosity on electrical charge is not.

Conventional Pulse-Jet Mode Results

Some preliminary conventional pulse-jet operation was carried out prior to the dust-cake mode experiments just described. These experiments were performed with the full nine-bag complement of polyester felt bags filtering DEF. The air-to-cloth ratio was 6 fpm (3 cm/sec) with an inlet dust concentration of 4 gr/ft^3 (9 g/m^3). Cleaning pulse pressure was 90 psi (620 kPa) and the time interval between successive cleaning pulses was 60 secs so that each row of three bags was cleaned on-line every 3 min. Total airflow through the baghouse was 250 acfm (7.08 m^3/min) implying an average upward linear gas flow between the hopper and the bags of 46 ft/min (14 m/min).

Only the duct precharger (Appendix 1) was used in these experiments and the conclusion reached in a series of 6-hour runs comparing precharger ON with precharger OFF performance was that the precharger had no significant influence on either collection efficiency or pressure drop.

This observation is consistent with the model of conventional pulse-jet filtration described in the Background section of this paper in which the filtration properties are depicted as more dependent on the retained dust load than on the dust freshly fed between cleaning pulses. The implication of that model is that the bag cleaning and the redeposition processes dominate the performance rather than a dust parameter such as inlet concentration. Variations in inlet concentration are less important than the areal mass density of the retained dust (Leith and Ellenbecker, 1980); the retained dust density depends more on cleaning parameters than inlet dust concentration (Dennis and Klemm, 1980).

Should the dominating effect of precharger operation prove to be a reduction in the rate of dust arriving at the bags, as the dust-cake mode measurements suggest, then the influence of precharger operation is predicted by these models to be small.

A new series of runs in the conventional pulse-jet mode is now underway. A major difference between this series and that previously carried out is that continuous operation around-the-clock over an extended period is planned, as was done in the shaker baghouse experiments reported by Hovis, et al., (1981). To accommodate this goal other modifications have been required:

1. the complement of bags has been reduced from nine to three--one bag per row, and
2. the total gas flow has been reduced from 250 acfm (7.08 m^3/min) to 125 acfm (3.54 m^3/min), raising the air-to-cloth ratio from 6 ft/min (3 cm/sec) to 9 ft/min (4.5 cm/sec)--the same as in the dust-cake pulse-jet work just described.

Air pressure in the pulse reservoir remains at 90 psi (620 kPa); the interval between successive pulses is 47 sec so that each bag is cleaned every 141 sec. The flyash concentration in the inlet remains at 4 gr/ft^3 (9 g/m^3).

One observation already apparent in this new series is the higher dust loads of DEF building up on the fabric compared to the SPS flyash loads. This result is surprising because of the higher ΔP's and K_2''s of the SPS flyash in the shaker experiments. But after 24-hr operation in the conventional pulse-jet mode, a virgin polyester felt fabric weighed in with more than 2-1/2 times as much DEF as did a similar virgin fabric operating with the same filtration parameters but using SPS flyash (432 g/m^2 DEF vs 154 g/m^2 SPS flyash).

Establishment of long-term operating equlibriums, with the precharger both ON and OFF, is now underway.

Conclusions

1. The recognized differences between conventional pulse-jet operation and dust-cake filtration imply a different role of dust electrical charge in the two processes.
2. Operating the pulse-jet equipment in a "dust cake" mode shows the dominant effect of charging the flyash with a corona precharger is to reduce the dust loads on the bags.
3. Initial precharger-ON measurements in the conventional pulse-jet mode of operation fail to identify any performance effect of dust charging.

References

1. Ariman, T. and D.J. Helfritch. "Pressure Drop in Electrostatic Fabric Filtration." Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. III, EPA-600/9-80-039c (NTIS PB81-144800), September 1980, pp.222-236.

2. Chudleigh, P.W. and N.W. Bainbridge. "Electrostatic Effects in Fabric Filters During Build-up of the Dust Cake." Filtration and Separation, July/August 1980, pp.309-311.

3. Cooper, D.W. "Mechanisms for Electrostatic Enhancement of Filter Performance." Invited paper presented to The Fiber Society and the Filtration Society Joint Symposium on Fibers, Electrostatics and Filtration, Princeton, NJ, November 14-15, 1979.

4. Donovan, R.P., et al. "Electrostatic Augmentation for Particulate Removal with Fabric Filters." 5th International Fabric Alternatives Forum Proceedings, January 1981, Scottsdale, AZ, American Air Filter, Louisville, KY.

5. Dennis, R. and H.A. Klemm. "Modeling Concepts for Pulse Jet Filtration." J. Air Poll. Cont. Assn., 30, January 1980, pp.38-43.

6. Dennis, R. and H.A. Klemm. "Recent Concepts Describing Filter System Behavior." U.S./Japan Scientific Seminar on Measurement and Control of Particulates Generated from Human Activities. Kyoto, Nov. 10-14, 1980.

7. Ellenbecker, M.J. and D. Leith. "Theory for Dust Deposit Retention in a Pulse-Jet Fabric Filter." Filtration and Separation, November/December 1979, pp.624-629.

8. Ellenbecker, M.J. and D. Leith. "The Effect of Dust Retention on Pressure Drop in a High Velocity Pulse-Jet Fabric Filter." Powder Technology, 25, 1980, pp.147-154.

9. Hovis, L.S., et al. "Electrically Charged Flyash Experiments in a Laboratory Shaker Baghouse." Presentation to the Third Symposium on the Transfer and Utilization of Particulate Control Technology, March 1981, Orlando, FL (this proceedings).

10. Iinoya, K. and Y. Mori. "Effects of a Corona Precharger and Relative Humidity on Filter Performance." Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. III, EPA-600/9-80-039c (NTIS PB81-144800), September 1980, pp.237-250.

11. Leith, D. and M.W. First. "Pressure Drop in a Pulse-Jet Fabric Filter." Filtration and Separation, September/October 1977, pp.473-480.

12. Leith, D. and M.J. Ellenbecker. "Theory for Penetration in a Pulse-Jet Cleaned Fabric Filter." J. Air Poll. Contr. Assn., 30, August 1980, pp. 877-881.

13. Leith, D., et al. "Performance of a High-Velocity Pulse-Jet Filter II." EPA-600/7-80-042 (NTIS PB80-183866), March 1980.

14. Oglesby, S. and G.B. Nichols. Electrostatic Precipitation, Marcel Dekker Inc., New York, NY (1978).

15. Turner, J.H. "EPA Research in Fabric Filtration: Annual Report on IERL-RTP In-House Program." EPA-600/7-77-042 (NTIS PB-267441), May 1977.

TABLE 1. DETROIT EDISON FLYASH FILTRATION IN THE PULSE JET (DUST CAKE MODE)

Charger Status	R.H. (%)	Filtration Time (min)	Total Dust on Bags (g)	Feed Rate to Bags (g/min)	Feed-Rate Ratio ON/OFF	K_2' Ratio ON/OFF
OFF	70	60	844	14.1	0.28	-
ON	70	120	483	4.0		
OFF	30	60	775	12.9	0.63	0.85
ON	30	120	972	8.1		
OFF	70	40	387	9.7	0.38	0.90
ON	70	80	295	3.7		

TABLE 2. SOUTHWESTERN PUBLIC SERVICE FLYASH FILTRATION IN THE PULSE JET (DUST CAKE MODE)

Charger Status	Relative Humidity (%)	Filtration Time (min)	Total Flyash Added (g)	Feed Rate to Bags (g/min)	Feed Rate Ratio (ON/OFF)	K_2' (in. of H_2O-min-ft/lb[m])*	K_2' Ratio (ON/OFF)
OFF	30	18.5	443	23.9	0.33	13.8	0.93
ON	30	40	312	7.8	0.34	12.9	0.98
OFF	30	13.2	304	23.0		13.2	
OFF	70	18.6	400	21.5	0.20	15.1	0.92
ON	70	40	169	4.2	0.20	13.9	1.12
OFF	70	9.0	189	21.0		12.4	

*1 (in. of H_2O-min-ft/lb[m]) = 10^4 sec^{-1}

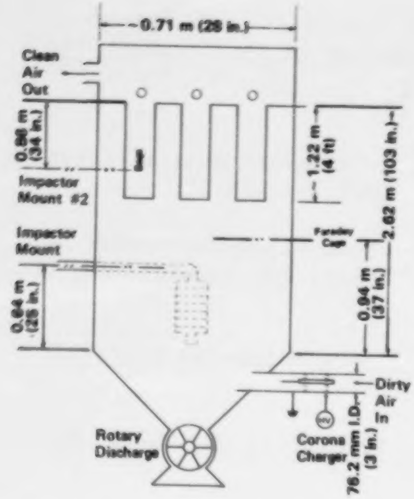

0.71 m (28 in.)
Clean Air Out
0.86 m (34 in.)
Impactor Mount #2
1.22 m (4 ft)
2.62 m (103 in.)
Faraday Cage
Impactor Mount
0.64 m (25 in.)
0.94 m (37 in.)
Dirty Air In
Rotary Discharge
Corona Charger
76.2 mm I.D. (3 in.)

Figure 1. Pulse jet schematic.

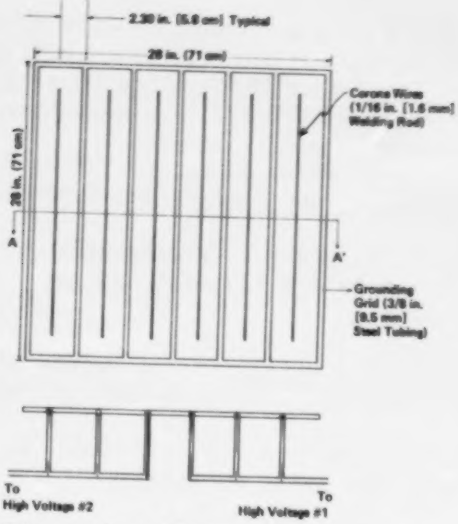

2.30 in. [5.8 cm] Typical
28 in. (71 cm)
Corona Wires (1/16 in. [1.6 mm] Welding Rod)
28 in. (71 cm)
A
A'
Grounding Grid (3/8 in. [9.5 mm] Steel Tubing)
To High Voltage #2
To High Voltage #1

Figure 2. Plenum precharger.

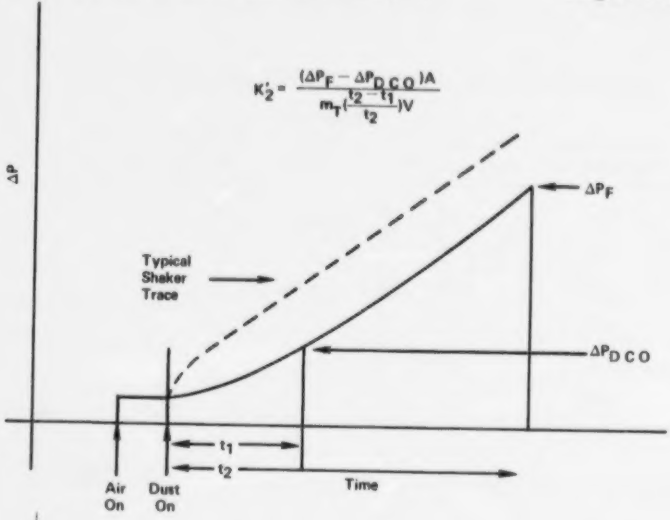


Figure 3. Pulse jet pressure trace (DC mode).

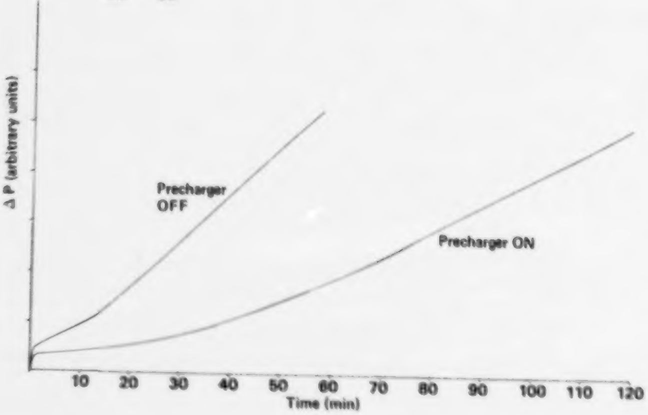


Figure 4. Pulse jet filtration of Detroit Edison flyash.

APPENDIX 1: PREDICTED PRECHARGER PERFORMANCE

A sketch of the duct precharger appears in Figure A1 along with typical current-voltage levels. All corona current is assumed to flow through the protruding short length, ℓ, of welding rod. For a typical experiment this length was 5-in. (12.7 cm) and was mounted coaxially within a 3-in. (7.6 cm) inside diameter duct. Current flow through other sections of the structure, such as the support mount to which the welding rod is attached, is ignored.

To calculate the charging-time constant, τ, of this precharger at typical power settings, an expression given by Oglesby and Nichols (1978, p.63) is used:

$$\tau = \frac{4\varepsilon_o}{N_o eb} = \frac{4\varepsilon_o}{\sigma} \qquad \text{(A1)}$$

where ε_o = permitivity of free space = 8.85×10^{-12} ($C^2s^2/kg\text{-}m^3$);

N_o = charge carrier concentration;

e = carrier charge;

b = carrier mobility; and

σ = electrical conductivity.

From the power supply current and voltage, the medium conductivity can be estimated as:

$$\sigma = \frac{J}{E_o} \qquad \text{(A2)}$$

where J = I/duct wall area adjacent to corona wire = $J/2\pi\ell r$;

E_o = V/r; and

I,V = power supply current and voltage.

Substituting the values from Figure A1 in Equations (A2) and (A1) yields:

$$\sigma = \frac{J}{E_o} = \frac{0.013\ A/m^2}{5.25 \times 10^5 V/m} = 2.51 \times 10^{-8} (\text{ohm-m})^{-1} \qquad \text{(A3)}$$

$$\tau = \frac{4\varepsilon_o}{\sigma} = \frac{4(8.85 \times 10^{-12})}{2.51 \times 10^{-8}} = 1.41 \times 10^{-3} s \qquad \text{(A4)}$$

The typical gas flow rate through the inlet duct is 125 acfm (3.54 m^3/min). This volume flow corresponds to a linear flow rate of approximately 44 ft/sec (13 m/s) which implies that the time required to pass by the 5-in. (12.7 cm) length of corona wire is about 9.8 ms. Using the charging expression from Oglesby and Nichols (1978),

$$q(t) = q_s \frac{1}{1 + \tau/t} \qquad \text{(A5)}$$

where $q(t)$ = particle charge;

q_s = particle saturation charge;

t = charging time; and

τ = charging time constant;

and the estimated values of t (9.8 ms) and τ (1.41 ms) just calculated, Equation (A5) predicts a $q(t)/q_s$ ratio of 0.87, implying that the flyash particles should achieve 87% of their saturation charge when traversing the precharger sketched in Figure A1. Doubling the volume flow through the inlet duct cuts the charging time in half. Thus, a total air-flow rate of 250 acfm (7.08 m^3/min) reduces charging time to 4.9 ms which, by Equation (A5), implies that particles will be charged to 78% of their saturation values.

The expression for saturation charge q_s, under field charging conditions, is given by Oglesby and Nichols (1978, p.63) as:

$$q_s = 12 \frac{\kappa}{\kappa + 2} \pi \varepsilon_0 a^2 E_0 \qquad \text{(A6)}$$

where κ = particle dielectric constant;

a = particle diameter; and

all other symbols are as before.

By dividing a flyash sample into increments according to size as in an impactor sampling, q_s can be computed from Equation (A6) for the mean diameter of each increment. Assigning appropriate weightings to each increment, the total saturation charge of a given mass of sample can be estimated.

Following this procedure yielded a saturation charge/mass estimate for the Detroit Edison flyash of 57 μC/g, assuming that $\kappa/\kappa+2$ in Equation (A6) is equal to 1. At 87% charging efficiency, the estimate reduces to about 50 μC/g. As measured by the Faraday cage, values of Q/M have typically been 0.7-1.1 μC/g with the precharger ON. When the precharger is OFF, Q/M ~0.1 μC/g.

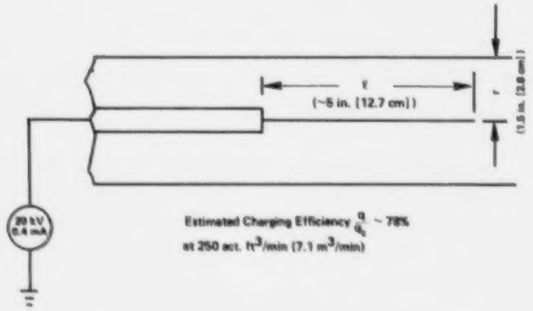

ℓ
(~5 in. [12.7 cm])
r
(1.5 in. [3.8 cm])
20 kV
0.4 mA
Estimated Charging Efficiency $\frac{q}{q_s}$ ~ 78%
at 250 act. ft^3/min (7.1 m^3/min)

Figure A1. Duct precharger.

ELECTRICALLY CHARGED FLYASH EXPERIMENTS IN A LABORATORY SHAKER BAGHOUSE

By: L.S. Hovis, J.H. Abbott
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

R.P. Donovan, C.A. Pareja
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, N.C. 27709

ABSTRACT

As has been demonstrated for numerous dust/fabric systems, increasing the electrical charge of the dust particles dramatically reduces the K_2' values of the dust cake formed by such particles. This demonstration has been repeated in a room-temperature-operated shaker baghouse, using redispersed flyash from both Southwestern Public Service and Detroit Edison with silicone-graphite finished fiberglass bags. The observed dependencies of this effect upon operating time and relative humidity are presented. Interpreting the results in traditional K_2' terms requires corrections for flyash collection by the precharger which is shown to vary with precharger cleaning techniques.

Prolonged operation with a charged flyash gas stream at 50 percent relative humidity causes the low K_2' values, characteristic of highly charged flyash, to gradually increase to the range characteristic of uncharged flyash. Increasing the operating relative humidity to 70 percent rapidly restores the low K_2' operation. These observations are interpreted in terms of flyash electrical resistivity and its role in the operation of the precharger of an electrically enhanced dust filtration system.

TEXT

Increasing the magnitude of the electrical charge on a dust sample improves its filtration properties by increasing its collectability (increasing the efficiency of the filter collecting it) and lowering its specific cake resistance, as has now been shown by many researchers (Chudleigh and Bainbridge, 1980; Ariman and Helfritch, 1980; and Iinoya and Mori, 1980). Commercial apparatus seeking to capitalize on this improved performance now exists (Helfritch, 1977 and 1979) even though the basic mechanisms producing this type of electrically enhanced performance are not well understood. The goal of the experiments to be reported here is to develop fabric filter performance models that include electrical charge as a parameter and permit the prediction of electrically enhanced performance. This goal is ambitious since only under severely restricted conditions can fabric filtration performance be predicted for the non-electrically enhanced case. Nonetheless this paper describes the initial EPA experiments toward that goal.

Apparatus

All experiments were performed in the one-bag shaker baghouse described by Durham and Harrington (1971). This system operates at room temperature and uses redispersed dusts of various types as a test material for bag performance measurements. Several modifications are worth noting, however. The variable speed dust feeder is now enclosed in a separate feed house, the humidity of which is controlled by an Inreco® humidifier. Thus, the entire hopper and its dust load are stored at the desired humidity. The flyash-laden stream passed to the baghouse draws its makeup air from this same humidity-controlled chamber.

A corona charging section has also been added to the top entry of the baghouse as illustrated in Figure 1. The high-voltage electrode consists of a steel tube positioned along the centerline of a section of the entry pipe. The steel tube is electrically isolated by Teflon® standoffs through which the high voltage power line is routed. On the downstream end of the tube, an adjustable length of 1/16 in. (1.6 mm) welding rod protrudes. Its dimensions control the corona discharge. The distance between the end of the corona wire and the top of the bag varies between 14 and 18 in. (36 and 46 cm).

A 1/4-in. (6 mm) line for drawing a sample through a Faraday cage is located immediately downstream of the corona wire. In the absence of flyash feed, no significant current is detected by the Faraday cage even when operating above the maximum corona power used in any of the experiments.

With typical flyash concentration in the inlet (~ 3 gr/ft^3 [6.9 g/m^3]), the charge/mass (Q/M) of the flyash increases by approximately one order of magnitude (to 2 to 5 μC/g) when the corona power is 15-20 kV, 0.1 to 0.2 mA. This operation constitutes the "charged" flyash condition used as a variable in the performance experiments. Charger-OFF (no high voltage to the corona wire) typically means the flyash Q/M is 0.2 to 0.5 μC/g, although excursions from this range occur periodically. The sign of the flyash charge with the corona ON is always negative, corresponding to the power supply polarity. Charger-OFF operation sometimes results in positive flyash charge but is not predictable.

Two types of flyash are used in these experiments: from the hopper of an electrostatic precipitator (ESP) at Detroit Edison and from the hopper of a baghouse at Harrington Station No. 2 Boiler (Southwestern Public Service). The Detroit Edison flyash (DEF) was further classifed by passing it through a laboratory ESP. Once loaded into the baghouse-feed hopper, it is dispersed into the dirty air stream, collected by the bag, dumped into the baghouse hopper, and eventually returned manually to the feed hopper from which the cycle is repeated. The size distribution of this DEF, after several months of such cycling, is shown in Figure 2. (These plots were actually made in the laboratory pulse-jet baghouse, which used the same flyash, and in the same recycling mode. The pulse jet permits an impactor to be inserted into the baghouse so that sampling losses are confined to the impactor inlet alone.)

No impactor analyses have been made on the Southwestern Public Service (SPS) flyash since it has been used only in the shaker baghouse. This flyash is the same as that described by Ladd, et al. (1980) and Lipscomb, et al. (1980).

The filter bags used in all tests reported here were silicone-graphite finished fiberglass, W.W. Criswell Style 445-04. These bags are similar to those installed initially at Harrington No. 2. Their properties and performance in the Harrington baghouse were discussed by Ladd, et al. (1980); Lipscomb, et al. (1980) evaluated this fabric, along with other fabrics in the EPA mobile baghouse operating on a slipstream from Harrington No. 1. Unused bag samples prepared for these latter tests were furnished to the EPA in-house facility by Lipscomb. These bags were cut and shaped to fit the shaker baghouse, resulting in a bag area of approximately 7.4 ft^2 (0.69 m^2). The bags were mounted with their texturized surface facing the flyash stream.

The shaker baghouse has a top entry through which the dirty-air stream from the feedhouse is pulled. A long 1-in. (2.5 cm) diameter hose connects the feedhouse to the top of the baghouse. At the top of the baghouse the gas stream passes through a flow straightener element shaped like a witch's hat, traverses the corona precharger section, and then enters the top of the vertically hung bag. A sealed hopper beneath the bottom of the bag catches all dust during filtration and cleaning. In-situ measurements show essentially no dust collection by the hopper during filtration--the hopper fallout in this configuration is essentially zero. For shake-cleaning, the bottom of the bag is attached to a tapered outlet section which is coupled by a flexible joint to the hopper entry pipe. The tapered section is oscillated by an eccentrically driven rod at 4 cycles/sec. The amplitude of the rod displacement from its center position is about 7/8-in. (2.2 cm).

The typical cleaning cycle used in most of the experiments reported here consists of a 1-min pause after the end of the filtration cycle, a 2-min shake-clean as described above, and finally a 1-min pause before the beginning of the next filtration cycle. For some data the shake-clean portion of the cycle was shortened to either 60 or 30 secs, primarily to minimize bag wear under special test conditions. This modification is assumed not to alter the cleaning significantly, based on beta backscattering measurements of SPS flyash removal during cleaning (Gardner, et al., 1981). These removal measurements suggest that virtually all flyash that is removed during the overall cleaning cycle is removed during the first 20 secs of the shake-clean, a conclusion similar to that reached earlier by Walsh and Spaite (1962) and by Dennis and Wilder (1975) although these researchers used different experimental techniques.

In the typical routine operation, pressure drop across both the bag and a venturi neck (to measure flow) is monitored continuously. In addition, special sensors have been incorporated for certain experiments. Among these sensors have been the previously mentioned beta gauge (Gardner, et al., 1981), an in-situ load cell for weighing the hopper dust, and various electrodes for measuring charge accumulation in or on the bag (Donovan, et al., 1980). These outputs will not be discussed further in this paper.

Periodic sampling of the inlet and outlet dust streams is also routine in the operation of the laboratory baghouse. The quantity of dust fed into the baghouse by the Acrison screw feeder is sampled daily. This feed rate is usually very stable so long as the hopper is above 10 percent capacity. The outlet dust concentration is also monitored during several filtration cycles per day by isokinetically drawing a sample from the outlet line and collecting it on a filter for weighing. Typically this outlet sampling takes place only during the forward filtration flow and extends over only one such cycle, but in any event is of at least 20-min duration.

Inlet dust Q/M is also sampled periodically, typically daily, through a port just downstream from the corona wire (Figure 1). This measurement consists of collecting a sample on a filter that is electrically isolated from ground. During sampling the charge accumulation on the filter is measured by a Keithley electrometer (in the charge measurement mode). The dust mass is determined by a post-sampling weighing and both a Q/M and a space-charge density (Q/volume of gas passed through the filter) are calculated. The total mass collected by the filter is reduced when the precharger is ON. The Q/M reported is that of the mass that is collected and the charge it carried with no correction attempted for any sampling bias that might be introduced by the charge.

Precharger operation was at predetermined values of either current or voltage. The corresponding power levels were recorded at the beginning of the experiments and monitored periodically through the runs but no continuous record of these levels was made.

Results

A test series was conducted with each of the two test flyashes. The SPS flyash series was conducted first and consisted of three separate sequential runs, each starting with a new bag which was operated around the clock over a time period of 2-3 weeks. One run with DEF then followed, again beginning with a fresh, unused fiberglass bag.

The test plan consisted of comparing performance, chiefly pressure drop, between precharger-ON and precharger-OFF operation. Implementation consisted of operating the baghouse at fixed conditions until an equilibrium was achieved, then switching the precharger to the opposite state and re-establishing equilibrium. Performance comparisons were then made between the two equilibrium states.

One question addressed immediately was the significance of the charge state of the initial flyash collected by the virgin fabric. The break-in period of a fabric is critical and under some conditions interactions occurring then can influence fabric performance far beyond this period of initial use (Davis, 1980). Specifically the desire to confirm that performance differences measured by the switching procedure outlined in the previous paragraph did not depend on break-in led to a comparison of two bag break-in histories--one broken in with the precharger OFF (Bag 1) and the second broken in with the precharger ON (Bag 2).

Each of these bags operated with a fixed 80-min filtration cycle followed by the cleaning cycle of 1-min pause, 2-min shake, and 1-min pause. Typical

ΔP traces during these cycles appear in Figure 3, one showing precharger ON; the other, precharger OFF.

The persistent observation of all the experiments, regardless of dust type, is contained in Figure 3--turning ON the precharger significantly reduces the rate at which ΔP increases with time. This conclusion holds for bags broken in with the precharger ON as well as for those broken in with the precharger OFF. Indeed the status of the precharger during break-in appears to be unimportant to the laboratory observations, as shown in Figure 4. The same general shaded bands of K_2' and ΔP_F (Figure 4) apply to both bags; hence the conclusion that ordering sequence is relatively unimportant for determining ΔP_F and K_2'.

In Figures 5 and 6 similar data are shown for the DEF. Here, only one bag was evaluated and the filtration period was extended to 180 minutes because of the lower values of K_2' and ΔP_F. As in Figures 3 and 4 the influence of turning ON the precharger is evident in this flyash system as well, although the K_2' values of the DEF are lower than those of the SPS flyash (indeed the precharger OFF values for DEF are about the same as those measured for the SPS flyash with the precharger ON).

Other researchers have attempted to interpret the reduced K_2' values of charged dust in terms of an increased dust-cake porosity (Cooper, 1979). While this effect may contribute to the flyash observations reported here, other factors prove to be more important. The K_2' data presented in Figures 4 and 6 have been calculated from the following expression:

$$K_2' = \frac{(\Delta P_F - \Delta P_E)}{C_i V^2 t_F} \qquad (1)$$

where ΔP_F = the pressure drop across the bag at the end of the filtration cycle;

ΔP_E = the effective pressure drop at the beginning of the filtration cycle (the intersection of the linear portion of the ΔP trace with the $t = 0$ axis);

C_i = dust concentration in the inlet;

V = the superficial filtration velocity (the gas-to-cloth ratio); and

t_F = the time of a filtration cycle.

In Equation 1, the factor $C_i V t_F$ represents the mass/area of the dust cake producing the change in pressure drop across the bag. Using Equation 1 is therefore equivalent to assuming that all dust fed into the baghouse ends up evenly distributed on the fabric. In particular the use of Equation 1 in conjunction with precharger-ON data is suspect, since flyash collected by the precharger section is not adequately accounted for. Rewriting Equation 1 as:

$$K_2' = \frac{(\Delta P_F - \Delta P_E)A}{m_T V} \qquad (2)$$

where A = the total fabric area; and

m_T = the total dust mass added to the fabric during the filtration cycle;

makes clear the fact that a change in the flyash ending up on the bag from that assumed by setting $m_T = C_I V t_F A$ changes the computed value of K_2'. Failure to include such corrections leads to K_2' errors. No such corrections have been made in the data presented in Figures 4 and 6.

To use Equation 2, which requires a measurement of m_T, the experimental procedure was changed to include a hopper weighing after selected shake-cleanings. In addition, in certain experiments, the precharger section above the bag was cleaned by manual rapping after the bag itself had been cleaned by the conventional mechanism. A crude mass balance could be carried out by dividing the incoming flyash into four possible destinations:

1. the hopper,
2. the outlet duct,
3. the bag, and
4. the precharger.

As mentioned previously, the hopper fallout proved negligible in this top-entry system. The flyash penetrating the bag to reach the outlet duct was assumed to be less than 1 percent and hence also negligible. The conclusion is that the two flyash weighings--that of the flyash shaken from the bag during the shake-clean portion of the cycle and that dislodged from the precharger section during manual rapping--should account for most of the flyash entering the baghouse during a given cycle.

Table 1 summarizes the results of such measurements carried out with the DEF. All measurements were made after a fixed 3-hour filtration cycle in which approximately 1170 g of flyash entered the baghouse. The amount of flyash ending up on the bag decreased with precharger voltage as shown. Using the actual mass of flyash collected on the bag as m_T in Equation 2 results in the corrected K_2' values shown while using Equation 1 yields the uncorrected K_2' values. These data show that when the precharger is cleaned each cycle, the reduced K_2' values portrayed in Figures 4 and 6 are attributable primarily to flyash collection by the precharger.

When, however, the precharger section is not cleaned and the collected flyash is allowed to accumulate, a steady state is reached in which the flyash leaving the precharger is nearly the same as the quantity entering. As shown in Table 1b, under operation with no precharger rapping, 90 percent of the flyash mass fed into the baghouse ends up on the bag. Corrected K_2' values calculated from Equation 2 now show a decrease when the precharger is ON. This mode of operation is that in which the data of Figures 4 and 6 were collected.

The conclusions emerging from these corrected K_2' measurements therefore are that with a regularly cleaned precharger, the dominant mechanism of reduced bag ΔP is flyash capture by the precharger. Without regular precharger cleaning, however, the reduced ΔP is still observed but cannot be attributed to precharger collection. A true dust-cake effect is one possible explanation, but precharger efficiency and performance must be monitored more carefully before conclusive statements can be made.

Certain instabilities were noted under the no-clean mode of operation with Bag 3, the third bag run with the DEF. Bag 3 operated in a constant ΔP_F mode--the shake-cleaning portion of the cycle was initiated when the ΔP across the bag reached 6.6 in. of H_2O (1.6 kPa). Filtration time becomes a variable in this operating mode rather than a fixed value as it was for the cycles sketched in Figures 3 and 5. Long-term operating stability in this mode was monitored by running the bag around the clock over a period of several weeks, the only interruptions being for insertion and removal of efficiency measuring probes. Precharger power was ON throughout and the precharger section was left unrapped.

As evident in Figure 7, the charge-enhanced operation had essentially disappeared by Day 8; that is, the early filtration time period was on the order of 170 minutes (Day 2) while the Day 8 filtration time decreased to 70-80 minutes. The corresponding K_2' values are equivalent to those of the corona-ON band (Figure 4) for the Day 2 operation and the corona-OFF band for the Day 8 operation, even though the corona power has actually been ON throughout.

That this deterioration in performance is caused by precharger inefficiency is suggested by the subsequent Day 12 observation (not shown) in which the longer filtration time (lower K_2') operation is restored by operating at 70 percent relative humidity. This dependence on relative humidity is interpreted as a flyash-resistivity effect, the added mositure serving as a "conditioning" agent which lowers the electrical resistivity of the flyash and restores the charging efficiency of the precharger.

Conclusions

1. When the precharger section is cleaned by manual rapping during each cycle, the dominant mechanism of the charge-enhanced performance is dust removal by the precharger so that the system should be modeled as a serial combination of a precharger ESP and a conventional fabric filter. This conclusion does not reject previous reports of K_2' reduction with increasing electrical charge as will be discussed in the following paragraph; it does imply that the contribution of any such true K_2' reduction is less than that attributable to the mass removal effect--at least for the experiments carried out in the EPA shaker baghouse with regular precharger cleaning.

2. If the precharger section is not cleaned, a significant enhancement continues to occur. Under these conditions, a steady state is reached between the dust entering the precharger and the dust leaving the precharger. The dust reaching the bag during any given filtration cycle then is approximately equal to that fed into the system so that the precharger collection efficiency is effectively zero. Under these conditions, enhanced filtration still occurs as is apparent by the mass-corrected values of K_2'. This mode of operation appears to be unstable as was illustrated by the loss of enhancement under long-term operation ($\simeq$8 days) at 50 percent relative humidity. That the enhancement could be re-established by raising the relative humidity to 70 percent suggests a flyash-electrical resistivity effect whereby the precharger operation has been restored by the use of a more conductive flyash.

In short, stable precharger operation is essential for stable enhanced filtration via charged flyash. Optimum precharger design is still under development. Whatever design is chosen, it will have to be operated and maintained along with the bags in order to realize and maintain enhanced filtration. The incorporation of a precharger upstream of a fabric filter therefore adds its own maintenance requirements to those of the baghouse. Although what constitutes either optimum or adequate precharger operation is not yet defined, the precharger probably will have modest performance requirements compared to those of a conventional electrostatic precipitator, and appears to possess the potential for improving overall baghouse performance whether as a pre-collector or a method of modifying dust-cake porosity or a combination of both.

Metric Conversions

1 in. of H_2O = 0.25 kPa; 1 gr/ft^3 = 2.29 g/m^3; 1 (in. of H_2O/ft/min)/lb/ft^2 = 10^4sec^{-1}.

References

Ariman, T. and D.J. Helfritch, "Pressure Drop in Electrostatic Fabric Filtration," Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. III, EPA-600/9-80-039c (NTIS PB 81-144800), September 1980, pp.222-236.

Chudleigh, P.W. and N.W. Bainbridge, "Electrostatic Effects in Fabric Filters During Build-up of the Dust Cake," Filtration and Separation, July/August 1980, pp.309-311.

Cooper, D.W., "Mechanisms for Electrostatic Enhancement of Filter Performance," Invited paper presented to The Fiber Society and the Filtration Society Joint Symposium on Fibers, Electrostatics and Filtration, Princeton, N.J., November 14-15, 1979.

Davis, W.T. and W.F. Frazier, "Conditioning of Fiberglass Fabric Filters for Improved Performance," TVA Report, October 1980, Department of Civil Engineering, University of Tennessee, Knoxville, Tennessee 37916.

Dennis, R. and J. Wilder, "Fabric Filter Cleaning Studies," EPA-650/2-75-009 (NTIS PB 240372), January 1975.

Donovan, R.P., J.H. Turner, and J.H. Abbott, "Passive Electrostatic Effects in Fabric Filtration," in Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, EPA-600/9-80-039a (NTIS PB 81-122202), September 1980, pp.476-493.

Durham, J.F. and R.E. Harrington, "Influence of Relative Humidity on Filtration Resistance and Efficiency of Fabric Dust Filters," Filtration and Separation, July/August 1971, pp.389-398.

Gardner, R.P., R.P. Donovan, and L.S. Hovis, "A Dual-Beam Backscatter Beta-Particle Gauge for Measuring the Filter Cake Thickness on Operating Bag Filters Independent of Position," presentation to the Third Symposium on the Transfer and Utilization of Particulate Control Technology, March 1981, Orlando, FL (this symposium).

Helfritch, D.J., "Performance of an Electrostatically Aided Fabric Filter," Chem. Eng. Prog., 73, August 1977, pp.54-57.

Helfritch, D.J., Apitron, Product Brochure, 1979, Apitron Division, American Precision Industries, 12037 Goodrich Dr., Charlotte, NC 28217.

Iinoya, K. and Y. Mori, "Effects of a Corona Precharger and Relative Humidity on Filter Performance," Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. III, EPA-600/9-80-039c (NTIS PB 81-144800), September 1980, pp.237-250.

Ladd, K.L., R. Chambers, S. Kunka, and D. Harmon, "Objectives and Status of Fabric Filter Performance Study," Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, EPA-600/9-80-039a (NTIS PB 81-122202), September 1980, pp.317-341.

Lipscomb, W.O., S.P. Schliesser, and S. Malane, "EPA Mobile Fabric Filter--Pilot Investigation of Harrington Station Pressure Drop Difficulties," Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, EPA-600/9-80-039a (NTIS PB 81-122202), September 1980, pp.453-475.

Walsh, G.W. and P.W. Spaite, "An Analysis of Mechanical Shaking in Air Filtration," J. Air Pollut. Control Assn., 12, No. 2, February 1962, pp.57-61.

Table 1. K_2' Values of Detroit Edison Flyash Corrected for Mass Loss to the Precharger* (3-hr filtration at 3 gr/ft^3 => 1170 g total feed).

a) Precharger Cleaned Each Cycle by Manual Rapping

Precharger Voltage (kV)	Dust Q/M (μC/g)	Dust on Bag (g)	Uncorrected K_2' (from Equation 1)	Corrected K_2' (from Equation 2)
0	-	1,152	5.4	5.5
10	1.5	999	4.8	5.6
12.5	1.9	615	3.7	7.0
15	3.1	615	3.0	5.7
17.5	3.5	413	2.5	6.9
20	-	443	1.7	4.4

b) Precharger Not Cleaned

Precharger Voltage (kV)	Dust on Bag (g)	Uncorrected K_2' (from Equation 1)	Corrected K_2' (from Equation 2)
17.5	1,060	2.5	2.7
17.5	1,071	1.9	2.1
17.5	1,012	2.1	2.5
17.5	900	2.3	3.0
0	908	5.4	6.1

*K_2' in units of $\left[\frac{\text{in. of } H_2O/ft/min}{lb/ft^2}\right]$

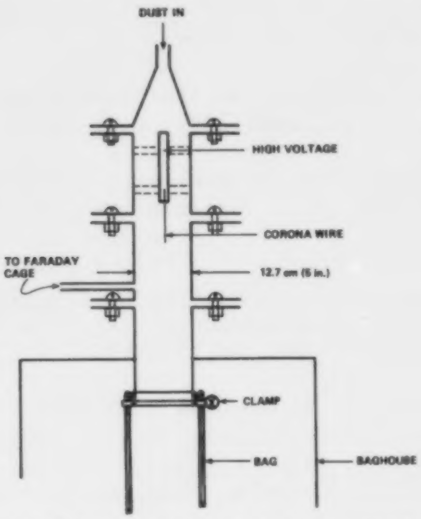
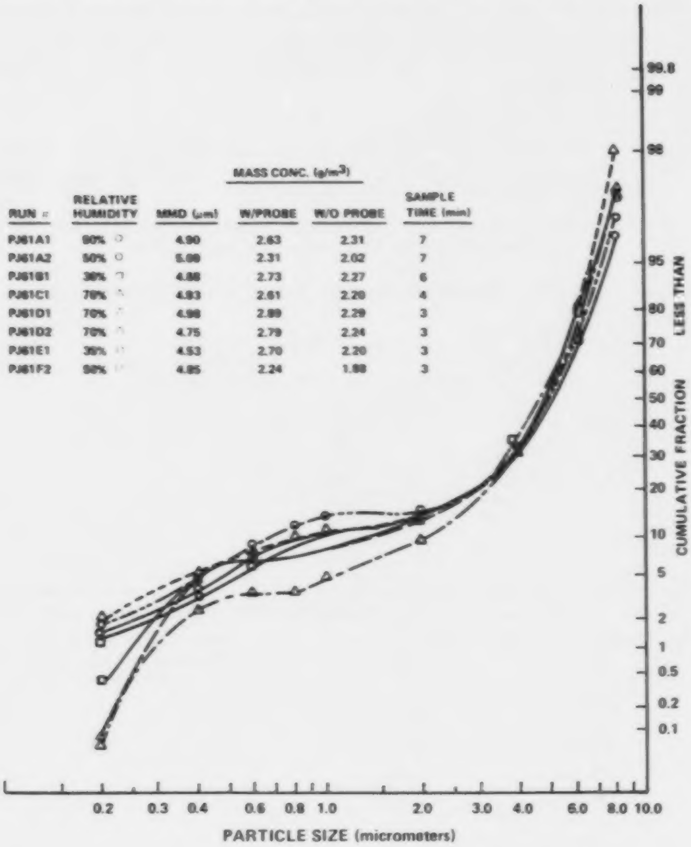

DUST IN
HIGH VOLTAGE
CORONA WIRE
TO FARADAY CAGE
12.7 cm (5 in.)
CLAMP
BAG
BAGHOUSE

Figure 1. Shaker baghouse inlet modified to accommodate a corona wire.



RUN #	RELATIVE HUMIDITY	MMD (μm)	MASS CONC. (g/m³) W/PROBE	MASS CONC. (g/m³) W/O PROBE	SAMPLE TIME (min)
PJ61A1	90% ○	4.90	2.63	2.31	7
PJ61A2	50% ○	5.08	2.31	2.02	7
PJ61B1	30% □	4.88	2.73	2.27	6
PJ61C1	70% △	4.83	2.61	2.20	4
PJ61D1	70% △	4.98	2.89	2.29	3
PJ61D2	70% △	4.75	2.79	2.24	3
PJ61E1	30% ◇	4.53	2.70	2.20	3
PJ61F2	90% ◇	4.85	2.24	1.88	3

Figure 2. In-situ impactor analyses of Detroit Edison flyash.

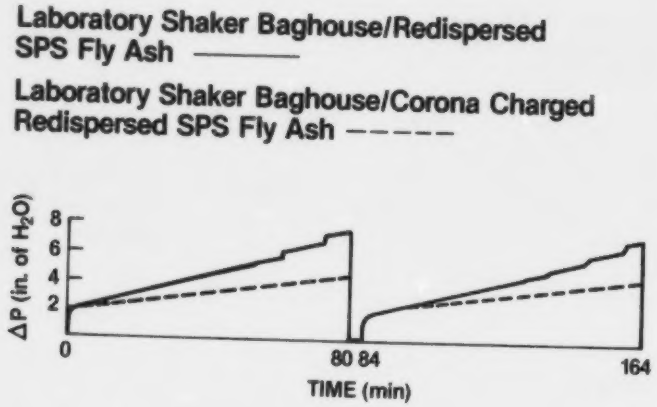


Figure 3. Reduced pressure drop of charged Southwestern Public Service flyash.

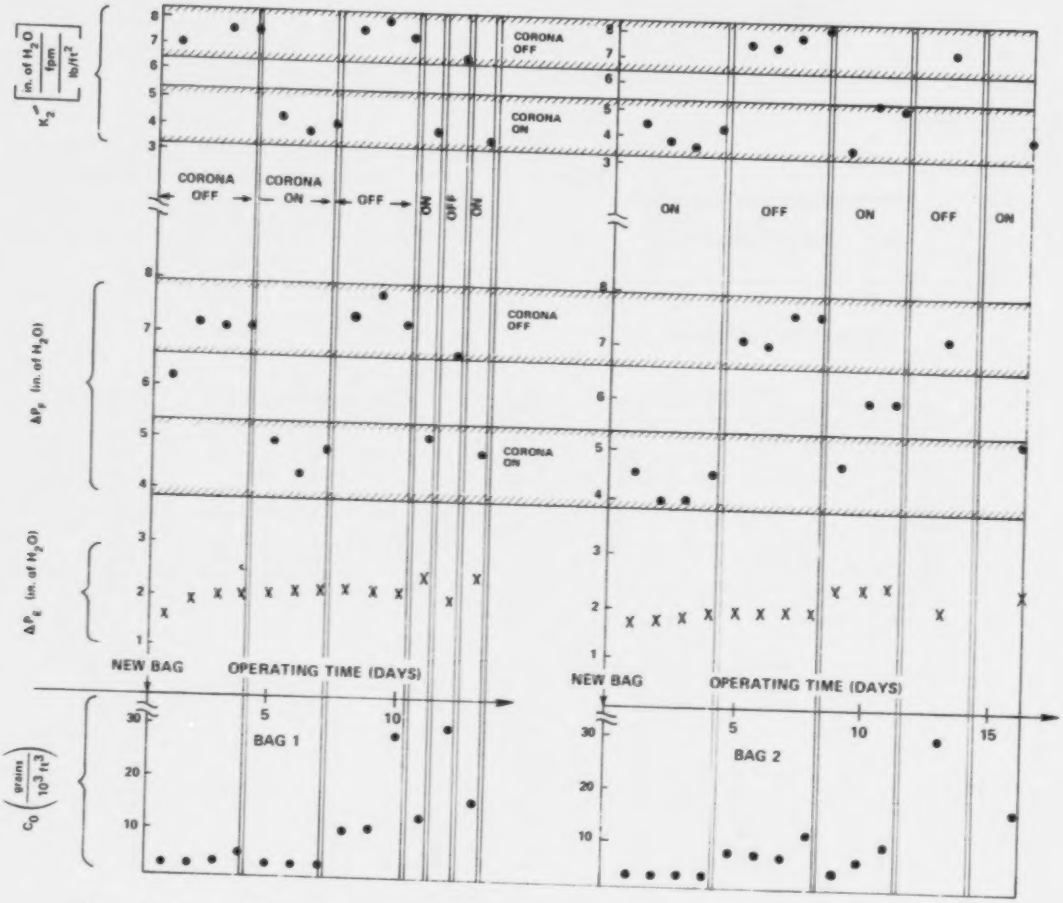


Figure 4. Filtration performance of Southwestern Public Service flyash/Criswell silicone-graphite fiberglass bag.

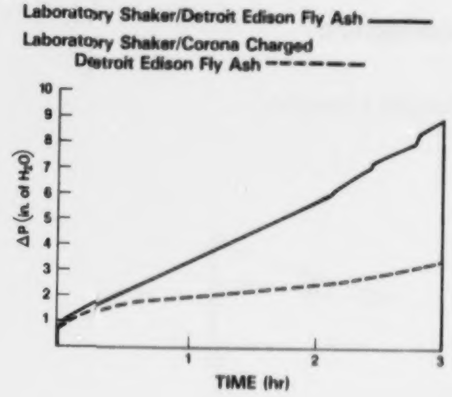


Figure 5. Reduced pressure drop of charged Detroit Edison flyash.

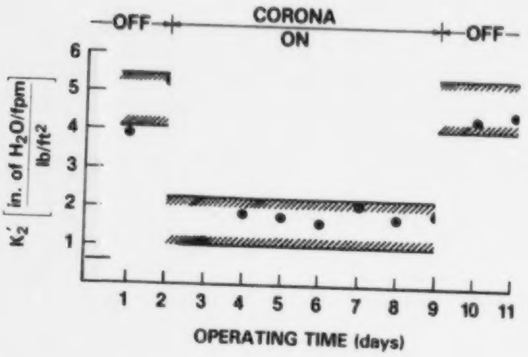


Figure 6. Specific cake resistance of Detroit Edison flyash.

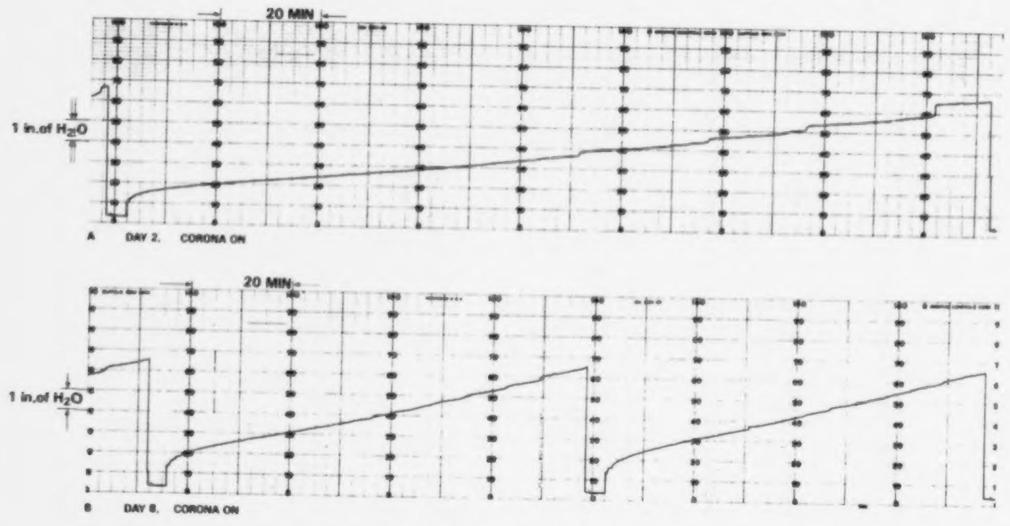


Figure 7. Degradation of electrically enhanced filtration of Southwestern Public Service flyash.

ELECTROSTATIC AUGMENTATION OF FABRIC FILTRATION

By: D. W. VanOsdell
Research Triangle Institute
P. O. Box 12194
Research Triangle Park, North Carolina 27709

G. P. Greiner
ETS, Inc.
3140 Chaparral Drive, S. W. (Suite C-103)
Roanoke, Virginia 24018

G. E. R. Lamb
Textile Research Institute
P. O. Box 625
Princeton, New Jersey 08540

L. S. Hovis
Industrial Environmental Research Laboratory
MD-61
U. S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

ABSTRACT

The concept of electrostatic augmentation of fabric filtration (ESFF) has been investigated at pilot scale. The pilot unit consisted of a conventional baghouse in parallel with an ESFF baghouse, allowing direct comparison. All results reported in this paper are for pulse-cleaned bags in which the electric field was maintained parallel to the fabric surface. The performance of the ESFF baghouse has been superior to the parallel conventional baghouse by several measures. The ESFF baghouse demonstrated: 1) a reduced rate of pressure drop increase during a filtration cycle, 2) lower residual pressure drop, 3) stable operation at higher face velocities, and 4) improved particle removal efficiency. These benefits can be obtained with only minor modifications to conventional pulse-jet hardware and at low electrical power consumption. The indicated ability to operate at increased face velocities with only modest expenditure for electrical hardware leads to very favorable economic projections.

INTRODUCTION

Electrostatic Augmentation of Fabric Filtration (ESFF)

A number of researchers have proposed and investigated various concepts for the use of electrostatic forces to improve fabric filtration. The work described in this paper used as a starting point work done by the Textile Research Institute (TRI).(1) Briefly, the TRI concept of ESFF consisted of the use of an electric field parallel to the fabric surface. The field was produced by raising alternate parallel wires to a high potential. Corona particle charging was not necessary. The electrode wires were on the dirty-gas side of the filter, in contact with, but not incorporated into, the fabric. .It was found that fabric surface characteristics had a major effect on the amount of enhancement possible. A low fabric surface density appeared to improve performance compared to a smooth, "cake release" fabric.

Figure 1 is a schematic of the TRI "harness," which was developed over the course of the TRI work and used at bench scale to evaluate the ESFF effect. As shown, the harness was tied to the outside of the bag and electrically connected so that alternate electrode wires were at high electrical potential. An important practical aspect of this design is that the cage within the filter bag must be insulated to prevent electrical shorting through the fabric. In general, the TRI investigation was carried out at ambient temperature with the bag operating at low pressure drops (about 0.25 kPa). The dust was a resuspended fly ash, with the bench pulse-jet unit cleaned on a 15-minute cycle.

The major advantages found for ESFF during the TRI investigation were a reduced rate of pressure drop increase and reduced particle penetration. A pressure drop ratio (PDR) was defined as:

$$\mathrm{PDR} = \frac{(\Delta P_f - \Delta P_r)_{\mathrm{ESFF}}}{(\Delta P_f - \Delta P_r)_{\mathrm{control}}} \qquad (1)$$

where ΔP is the pressure drop across the bags: f refers to the final state (just prior to cleaning), r refers to the residual state (just after cleaning), and control refers to a baghouse without electrical enhancement.

For an idealized filter cycle in which the bag pressure drop increases linearly with time at constant dust loading from ΔP_r to ΔP_f, it can be shown that:

$$\mathrm{PDR} = \frac{(K_2)_{\mathrm{ESFF}}}{(K_2)_{\mathrm{control}}} \qquad (2)$$

where K_2 is the specific cake resistance. PDR, then, is the ratio of the flow resistance of a dust cake collected by an ESFF system to that of a conventional fabric filter.

The Program

A program to evaluate ESFF at pilot scale is being carried out by a team consisting of the Research Triangle Institute (RTI), ETS, Inc., and TRI under contract to the U.S. Environmental Protection Agency. RTI, prime contractor, has directed the technical effort and performed electrical hardware development and construction. ETS, Inc., designed, built, and is operating the pilot unit.

The pilot unit will be operated in both pulse-jet cleaning (outside collection) and reverse-air cleaning (inside collection) modes. The program has been underway for about one and a half years. Most of that time has been spent in the pulse-jet operating mode; thus, all of the data reported in this paper are from pulse-jet operation. The principal parameters of the study have been pressure drop, mass removal efficiency, and removal efficiency by particle size. In addition, an economic analysis of the ESFF concept has been conducted. The program is presently continuing with the baghouses in the reverse-air operating mode.

EXPERIMENTAL SYSTEM

Pilot Baghouses

The pilot plant which was designed and built to investigate ESFF consists of two identical baghouses operating in parallel from a flue gas slipstream. One baghouse is electrostatically augmented, while the other is not. Figure 2 is an isometric drawing of the pilot unit. Each baghouse can accept up to 13 pulse-cleaned, 11.4 cm (4.5 in.) bags, each 244 cm (8 ft) long. Each pilot baghouse is about 85 cm (33 in.) square and 4.3 m (14 ft) high. Construction is carbon steel throughout. Three inches of insulation was used on both the baghouses and on all ductwork. The pilot units are fairly typical of the smallest industrial unit with two exceptions: 1) access doors were added on three sides of the baghouses, and 2) center-to-center bag spacing was increased slightly to allow clearance for the electrical hardware.

We feel that the use of parallel control and experimental units has made the difference between success and failure for the ESFF program. As is described below, the dust source has been highly variable, and it would not have been possible to speak with confidence about the experiment if we had operated serially, even with much more sophisticated instrumentation. Baghouse performance has been good. Additional baghouse insulation, wall heaters, and improved door seals were added during the checkout period to correct a low temperature problem. Otherwise, the baghouses performed as designed.

The pilot unit was installed on a slipstream from an industrial boiler house. Four pulverized coal boilers are in use with a normal load of about 160,000 kg/hr (350,000 lb/hr) of steam. The coal fed to the boilers changes frequently, with sulfur content varying from less than one percent to about two percent and ash content ranging from five to 15 percent. The boilers are sometimes co-fired with oil. Inlet dust loadings at the pilot plant have varied from 0.6 to 5 g/scm (0.25 to 2 gr/scf); 0.7 g/scm (0.3 gr/scf) is typical.

High Voltage Electrical Hardware

The electrical requirements of the ESFF system were relatively low. The power consumption measured by TRI (and since confirmed in the pilot unit) was about 1 W/m^2 (~ 0.1 W/ft^2). For comparison, energy requirements for gas moving at 3 cm/sec (6 ft/min) and 0.25 kPa (1 in. H_2O) are about 10 W/m^2 (~ 1 W/ft^2). At a potential difference between electrodes of 10 kV, one pilot unit bag required about 100 μA of current. The entire 13-bag complement, under normal conditions, requires less than 1.3 mA at 10 kV.

The electrical system used at the pilot unit consisted of a variable DC power supply (0 to 20 kV at 5 mA) for each of five power supply networks. Voltage was the controlled variable. Current and primary voltage were measured separately in each network. Current limiting and meter protection circuits were also used. The pilot unit was operated with no more than five bags and, consequently, only one bag on each network.

As described earlier, the TRI electrode "harness" consists of an array of small diameter vertical wires glued to horizontal yarns. The entire assembly was tied to the outside of the bag. Several problems were inherent in this design. The "harness" had the potential of restricting bag cleaning, was relatively fragile and difficult to install, presented materials problems in the high temperature flue gas environment, and required an insulated cage. In spite of these anticipated difficulties, harnesses were constructed for the pilot unit and were used to collect a significant portion of the data which is presented in this report. From the standpoint of operating a research pilot plant, the failures of the insulating coating on the cages and of the harness adhesive were the most significant problems. The materials used deteriorated within one to two months and required frequent attention.

The problems discussed above were largely overcome with the design and construction of a new electrode assembly. The electrodes were moved to the clean side of the bag and performed the dual function of cage and electrodes (Figure 3). Early laboratory data taken by TRI indicated that performance with this electrode arrangement would be reduced from that possible with the outside harness. Pilot plant results for the two designs have been essentially identical, however. The inside electrodes have now been used successfully for several months.

PILOT UNIT OPERATION

Pilot Unit Checkout/Bag Conditioning

The initial portion of the pilot unit test program was intended to demonstrate the crucial point that the two baghouses really were parallel units with identical inlets. To accomplish this, both houses were operated as standard fabric filters. After collecting enough data to be confident that the two baghouses were comparable, the test bags were installed. Four bags were installed in each baghouse; the electrical harnesses were installed on the bags in the ESFF baghouse. The bags were broken in at a face velocity of 1 cm/sec. Following the conditioning phase, the face velocity was raised to 3 cm/sec and the test program was initiated.

Test Program

Normal operating procedure was to conduct the test program during the day and to leave the baghouses on automatic operation overnight and on weekends. Several cleaning cycles were used during the test program; the face velocity was varied between 1 and 5 cm/sec. Operation was evaluated at field strengths between 0 and 5 kV/cm. Both the TRI harness and the clean-side cage/electrode described earlier were used to produce the electric field. Three fabrics were tested: 1) 23 oz Teflon® felt, mechanically napped to reduce the surface density; 2) 17 oz Teflon® felt, an experimental fabric; and 3) 17 oz woven glass fabric, ten percent Teflon® B finish, bulked in the fill yarn.

RESULTS AND OBSERVATIONS

Observations

Visually, the dust cake was somewhat thinner near the electrodes; this was true for both outside and inside electrodes. The outside harness continued to function even with a dust cake several times the electrode diameter on the bag. Cleaning of the bottom half of the bag was restricted by the harness, however. We were not able to resolve whether a very thick dust cake would reduce the ESFF effect, although some data indicated reduced performance after several hours without cleaning.

Normal, "good" operation of the ESFF baghouse required a current of only 1 to 10 μA at 8 to 10 kV on the electrodes. Variation in dust loading and normal boiler variations did not adversely affect operation. High dust loadings, for instance, caused high pressure drops or more frequent cleaning for the baghouses, but the ESFF baghouse retained its advantage. Dust characteristics do affect ESFF operation, however. Operation below the acid dew point was not possible because of high dust conductivity. In addition, short periods of high bag current (and reduced ESFF effect) due to dust properties have occurred two or three times. The ESFF baghouse recovered after cleaning. The cause of these upsets has not been determined, but soot and/or excessive carbon in the ash is suspected.

Rate of Pressure Drop Increase

The most obvious of the effects of ESFF is that of a reduced rate of pressure drop increase for a given dust loading rate. This is the effect which has been reported extensively by TRI. Figure 4 presents data from one cleaning cycle for the pilot baghouses. There is an evident difference in the rate of pressure drop increase. Expressed as PDR, the difference is even greater. The pressure drop in the control baghouse is not linear initially but becomes so after the cake has formed. The ESFF trace does not exhibit a cake repair period. Other data do show a cake repair period for the ESFF baghouses, although it is generally not as pronounced as that for the conventional baghouse.

Figure 5 is a presentation of PDR data as a function of average electric field. Teflon® felt and fiberglass bag data are included. A curve representing the performance of the TRI bench-scale baghouse is also presented. For the Teflon® felt bags, the pilot unit data are very similar to the TRI data in spite of markedly different operating conditions. The fiberglass bags, which do not have the low density surface characteristic of the Teflon® bags, do not exhibit as great an ESFF effect. It is worth noting that inlet mass loadings and hopper dust weights have remained about the same for both baghouses.

Residual Pressure Drop

The data presented in Figure 4 exhibit another of the ESFF effects, a lower residual pressure drop. The residual pressure drop of the ESFF unit was 20 to 80 percent of that of the conventional baghouse operated under identical conditions. It was possible through multiple off-line cleaning to return both baghouses to essentially the same residual pressure drop, but the residual pressure drop difference soon returned once normal operation was resumed.

Stability at Increased Face Velocity

The pilot unit has shown that the ESFF baghouse can be operated without blinding at a higher face velocity than can a conventional baghouse. Figure 6 presents some data which clearly show the improved performance possible with the ESFF baghouse. At 4 cm/sec, the conventional baghouse pressure drop became too high for the pilot unit blower, and the gas rate was actually dropping off at the high pressure drop. Mass collection efficiency decreased at high face velocities, as expected.

Particle Collection Efficiency

The pilot unit data indicate an increase in size dependent particle collection efficiency with the ESFF baghouse. Figure 7 is a plot of fractional penetration as determined by multiple cascade impactor tests. The ESFF baghouse shows consistently better collection efficiencies over the range 0.4 to 4.0 µm during the test period. However, penetrations are also influenced by more frequent cleaning of the conventional baghouse, so the improvement may not be because of improved collection as much as reduced losses through the cloth. Mass efficiency data have not shown a clear advantage for the ESFF baghouse.

Economics

The capability to operate at an increased face velocity for a particular dust gives the ESFF concept a large cost advantage over conventional fabric filtration. Compared to a conventional baghouse operating at 2 cm/sec (4 ft/min), an ESFF baghouse operating at 3 cm/sec (6 ft/min) might be expected to control the same emission problem for a 30 percent lower total annual cost. It may be possible to operate at 4 cm/sec (8 ft/min) as shown in Figure 6 at even lower cost.

CONCLUSIONS

ESFF as developed in the laboratory has been transferred successfully to a pilot unit on coal-fired boiler flue gas. The ESFF baghouse can be operated at increased face velocities compared to a conventional baghouse on the same flue gas. Other manifestations of the effect of the electric field on the dust collection are a reduced rate of pressure drop and a reduced residual pressure drop for an ESFF baghouse operated at the same face velocity as a conventional baghouse. In addition, at constant face velocity, particulate control is improved by the use of ESFF.

RECOMMENDATIONS

Pulse-Jet Baghouse

Although the initial pilot plant experience has been very positive and may be commercially viable, additional development work is required. Scale-up has not yet been investigated, nor truly long-term operation, and additional engineering effort is sure to be required in these areas. In addition, work is needed in the areas of cage insulators and the entire electrical system to reduce operator involvement and improve reliability. The use of different fabrics and application to other dust control problems are also subjects that should be investigated.

Reverse-Air Baghouse

The use of ESFF in reverse-air baghouses has not been tested at pilot scale. Bench work at TRI has been somewhat successful. The woven glass fabrics normally used do not have favorable surface characteristics, although they do exhibit an ESFF effect. In addition, the clean-side electrode/cage which was very desirable for the pulse-jet unit may not be best for the reverse-air system. The indicated need, then, is for development of fabric/electrode combinations that are optimal for ESFF. We will be working on this matter during the continuation of the pilot unit program.

ACKNOWLEDGEMENTS

This work was supported by Contract No. 68-02-3186 from the EPA Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. The assistance provided by E. I. DuPont de Nemours and Company, Inc., is gratefully acknowledged. The pilot unit was located at their Waynesboro, Virginia, plant and Teflon® fabric was donated to the test program by DuPont.

ENDNOTES

1. Lamb, G. E. R., and P. A. Costanza. A Low-Energy Electrified Filter System. Filtration and Separation. 17:319, 1980.

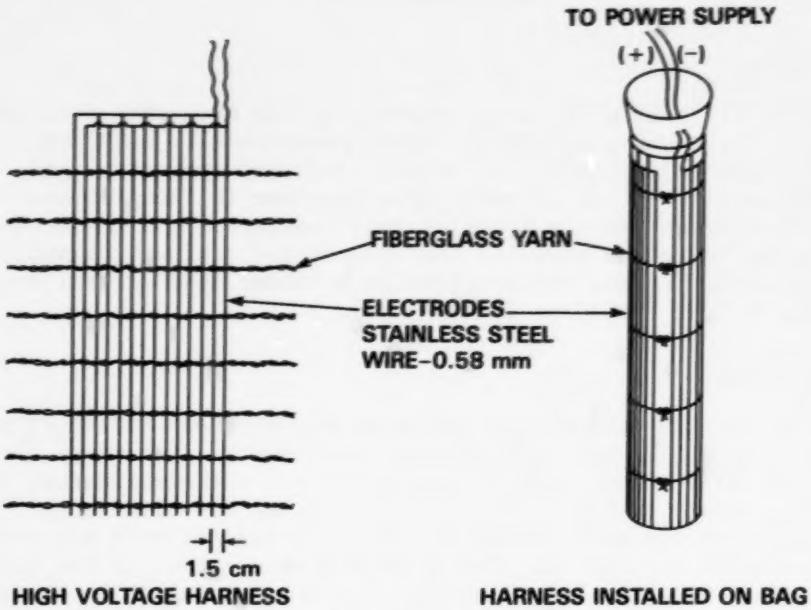

TO POWER SUPPLY
(+)
(-)
FIBERGLASS YARN
ELECTRODES
STAINLESS STEEL
WIRE-0.58 mm
1.5 cm
HIGH VOLTAGE HARNESS
HARNESS INSTALLED ON BAG

Figure 1. TRI high voltage harness.

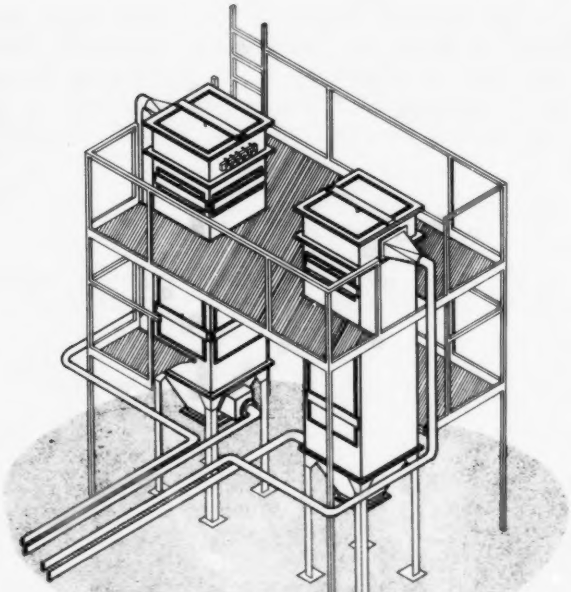


Figure 2. ESFF pilot unit.

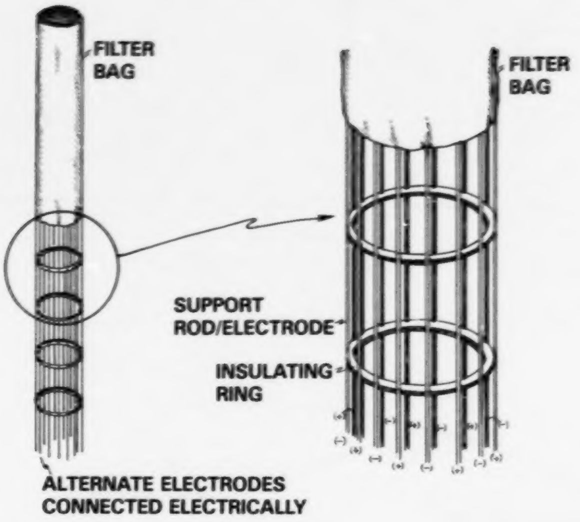

FILTER BAG
FILTER BAG
SUPPORT ROD/ELECTRODE
INSULATING RING
ALTERNATE ELECTRODES CONNECTED ELECTRICALLY

Figure 3. Inside electrodes-cage assembly.

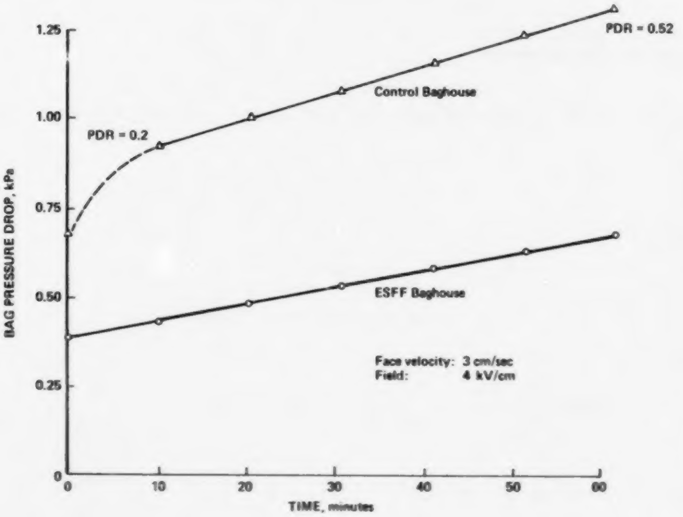


Figure 4. Bag pressure drop performance-single cycle.

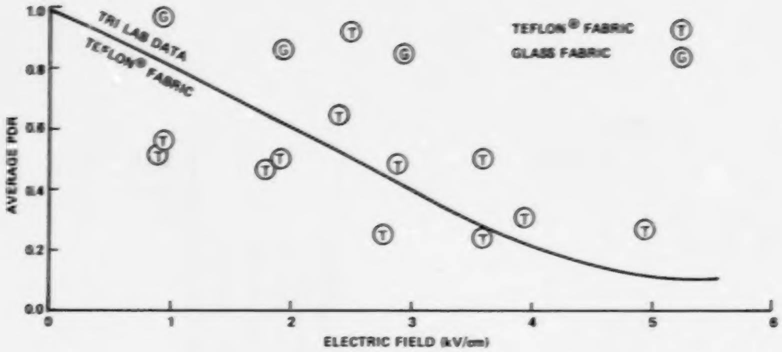
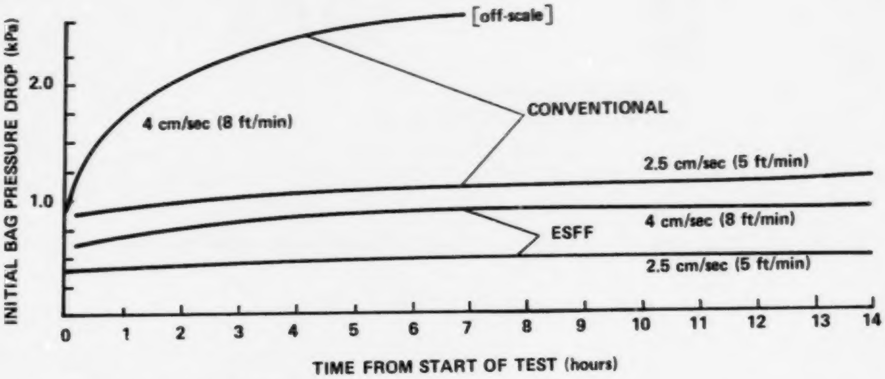


Figure 5. Pilot plant PDR data.



Note: Each test period preceded by multiple-pulse bag cleaning

Figure 6. Pilot unit performance at two face velocities.

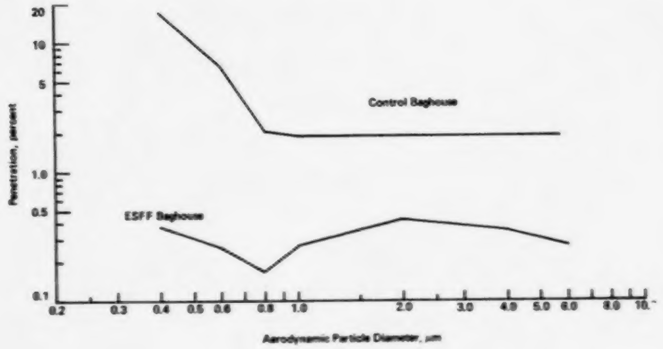


Figure 7. Size dependent particle penetration.

FABRIC WEAR STUDIES AT HARRINGTON STATION

By: Richard Chambers, Kenneth Ladd, and Sherry Kunka
Southwestern Public Service Company
P. O. Box 1261
Amarillo, Texas 79170

Dale Harmon
Industrial Environmental Research Laboratory
Environmental Protection Agency
Research Triangle Park, North Carolina 27711

ABSTRACT

The performance and service life of filtration fabrics in the utility industry is a subject of interest to many fabric filter users. Southwestern Public Service Company (SPS), among several other utilities, has developed a fabric evaluation program in conjunction with an Environmental Protection Agency (EPA) study being done at SPS's Harrington Station. This paper will discuss SPS's experience with fabrics and some of the conclusions that have been drawn.

Among the topics addressed will be:

1. The use of systematic physical testing on fabrics to monitor fabric wear and eventually predict fabric life.
2. An analysis of fabric wear mechanisms at Harrington Station.
3. Fabric failures by compartment position.
4. Controlling fabric wear by reducing shaker amplitude.

INTRODUCTION

Fabric filtration used in association with coal-fired utility boilers remains a relatively new air quality control technique. One of the most critical aspects of a successful fabric filter application is proper fabric selection. To date, however, conclusive fabric performance data has been unavailable to those involved in fabric selection for baghouse installations. Performance trends for a variety of fabrics are now beginning to emerge from a study being conducted by Southwestern Public Service Company (SPS) for the United States Environmental Protection Agency (EPA).

SPS is an electric utility based in Amarillo, Texas. The Company provides electricity to a 117,000-square kilometer (45,000-square mile) service area. Traditionally a gas-fired utility, SPS began its switch to coal-fired generation in 1976 when Harrington Station Unit 1 was put into service. Harrington Station is located approximately 8.1 km (5 miles) north of Amarillo. The facility consists of three 360 MW units. Unit 2, in 1978, was the first new electric utility boiler to be equipped with a fabric filter system for emission control. The boiler utilizes pulverized, low sulfur Western coal to produce 1,220,000 kg (2,688,000 lb) steam/hour. Flue gas from the boiler flows through the preheater directly through the fabric filter system and then out the stack.

The fabric filter system (or baghouse) is a Wheelabrator-Frye, Inc. (WFI) structural baghouse with shake/deflate cleaning. It consists of 28 compartments with 204 bags per compartment for a total of 5,712 bags; each bag is 0.3 m (11.5 in.) in diameter and 9.3 m (30 ft, 6 in.) long. The baghouse was specified at 2,800,000 m^3/h (1,650,000 acfm) of flue gas at 156°C (313°F), thus yielding a design air-to-cloth ratio of 3.17 to 1 (gross) or 3.4 to 1 (net). Harrington's Unit 3 is equipped with a WFI fabric filter which also employs shake/deflate cleaning. The Unit 3 baghouse, however, has four more compartments which yield air-to-cloth ratios of 2.78 to 1 (gross) and 2.98 to 1 (net).

Fabric Testing Results

Immediately following the rebagging of the Harrington Unit 2 fabric filter system, a fabric evaluation program was initiated for the new fabrics. The purpose of this program was to evaluate the wear characteristics and through-put for each of the fabrics under test in the unit. Table I shows the fabrics being evaluated.

TABLE I. Test Fabrics

Criswell 442-57DC2	0.34 kg/m^2	(10 oz/yd^2)	10% Teflon coating
Criswell 449-57DC2	0.48 kg/m^2	(14 oz/yd^2)	10% Teflon coating
Criswell 449-I580	0.48 kg/m^2	(14 oz/yd^2)	Silicone/graphite/ Teflon coating
Criswell 449 COF	0.34 kg/m^2	(10 oz/yd^2)	Proprietary coating
Menardi Southern 601-T	0.34 kg/m^2	(10 oz/yd^2)	10% Teflon coating
Globe-Albany Allspun Nomex	0.19 kg/m^2	(5.5 oz/yd^2)	Permaguard coating

In order to examine the various fabrics for wear, samples were removed from each of the test compartments on a periodic basis and sent to Environmental Consultants, Inc., for evaluation. Each sample was subjected to the following tests:

1. Breaking strength.
2. Mullen Burst.
3. MIT Flex -0.08 cm (0.03-in.) jaw @ 1.8 kg (4 lb).
4. Loss on ignition @ 650°C (1200°F).
5. Permeability.

According to the testing program conducted by Environmental Consultants for SPS, the weakened area along the most severe fold lines were the ones to be tested for mechanical strength rather than the stronger areas away from the fold lines. SPS believes that testing results obtained in this manner are more representative of the rate of decay in mechanical properties for a material since it will be the weakened areas that will determine the fabric life.

The results of Mullen Burst and breaking strength testing for each of the fabrics are shown in Figures 1 and 2. The 0.48 kg/m^2 (14 oz/yd^2) materials show much higher initial values for both Mullen Burst and breaking strength than the 0.34 kg/m^2 (10 oz/yd^2) fabrics, yet the rate of decay of these values is seen to be much higher. The higher initial values are due to the stronger fill yarn construction of the heavier fabrics while the difference in the rate of decline of the Mullen Burst and breaking strength is due to the different reaction of the fabrics to the baghouse environment and wear during the cleaning process.

On both plots, the highest initial values are for the proprietary Cris-O-Flex (COF) coated material. This is due to the fact that the fabric was not heat-cleaned prior to application of the coating. Since heat cleaning weakens the fabric to some extent, the COF-finished material has the initial advantage. This advantage is seen to decline, however, as all three of the 0.48 kg/m^2 (14 oz/yd^2) materials appear to have similar Mullen Burst values after a year in service.

Nomex, the only synthetic fabric in service, is shown on each of the plots at the bottom. This synthetic material, having inferior tensile properties to glass, nevertheless excells in the critical area of flex strength.

Aside from showing some different characteristics of fabrics of different weight, the Mullen Burst and breaking strength plots are disappointing in that there is nothing in the appearance of these curves to indicate that two of the test fabrics have reached termination of their useful life. The only indication of incipient failure obtained from the fabric testing results is shown on the MIT Flex plot in Figure 3. Here the reduced MIT value (MIT Flex/Initial MIT Flex, M/M_o) is plotted vs. service life. An indication of incipient failure is obtained by looking at the steep slope and low values for M/M_o for the 449 COF and 449-I580 fabrics. Both these fabrics are scheduled to be replaced due to the high failure rate at Harrington. That the MIT Flex tests should correlate best with the progress of fabric wear is certainly understandable since, of all the testing methods, the MIT Flex most accurately duplicates what the fabric undergoes during cleaning.

The existence of a critical value for M/M_o can be inferred from the simultaneous failure of the two fabrics as they approach the same reduced MIT Flex value (~0.07). If such a critical value exists at which termination of fabric life can be determined, it should become evident as the remainder of the test fabrics fail.

The data for Nomex is shown on the reduced MIT Flex plot but is not directly comparable to the glass fabrics since the test conditions were not the same. The MIT values for Nomex were obtained with a 2.3 kg (5-lb) weight instead of the usual 1.81 kg (4-lb) weight used for glass in order to generate numbers in a reasonable amount of time. The Nomex data is interpreted such that the fabric appears to yield acceptable remaining life and is in no way inferior to the glass materials. A recent paper titled "SPS Experience With Fabric Filtration" presents a more detailed discussion of the correlation between fabric testing results and actual operating conditions (1).

Failures by Compartmental Position

Any given section of bags within a compartment would be expected to have roughly the same failure rate as any other section of bags, all things being equal. In the case where bag failures are not equally distributed throughout a compartment, the cause of higher failure rates should be identified and eliminated, if possible, to save costly bag replacements and to allow faulty design concepts to be identified and eliminated.

To analyze the failure rate by compartment position at Harrington Station, the failures that have occurred to date have been superimposed onto a single plot by thimble position as shown in Figure 4. Two types of failures have been noted. Any small hole in a fabric is referred to as a "pinhole;" whereas, a large section ripped out of the fabric is shown as a "blowout."

The pinhole type failure is by far less prevalent now than during the first year of operation where it was the main failure type with the original fabric. These initial failures were thought to be due to fabric stretching resulting in a lack of tension and blousing over the thimble. The data indicate that there is no discernible pattern to the pinhole type of failure. Therefore, in Figure 4, only the blowout location is shown. The blowout failures definitely appear to occur more often in certain locations. The outside two rows account for 73 percent of all the blowout failures. Calculating the failures per thimble position for the outside two rows yields 0.91 failures per thimble vs. an overall average of 0.39.

Narrowing the failure area to the four corner areas two bags deep and five bags wide yields the failure rate shown in Figure 5. The two areas adjacent to the interior wall are seen to have the greatest failure rates with 1.8 and 1.2 failures per thimble compared to 0.21 for thimbles not in the corner areas. The corner areas adjacent to the outside walls also show significantly higher failure rates with 0.8 and 0.7 failures per thimble position. Factors contributing to these higher failure rates are thought to be hopper shed plate design and turbulent flow distribution in the ash hopper.

Failure Mechanisms in Filtration Fabrics

The two fabric styles undergoing premature failure at Harrington, Criswell's 449 COF and 449-I580, appear to be experiencing a wear pattern that is typical of the other fabrics being tested except that these two fabrics are damaged to a much greater degree. The typical wear pattern consists of a severely abraded area along a fold line in the fabric originating at the top and proceeding down the fabric approximately one-third the length of the bag. Along these abraded fold lines (called "wooley worms") pinhole failures occur at irregular spacings. A single bag may have as few as two such lines or as many as six. Eventually, failure will occur in the 0.48 kg/m^2 (14 oz/yd^2) fabrics of these "wooley worms" as a vertical split up to several meters (feet) long. The lighter, Teflon-coated fabrics, however, most often exhibit a rectangular-shaped blowout where the fabric appears to have had a section of cloth cut out of it. This behavior is believed to be due to the weaker warp yarn construction of the 0.34 kg/m^2 (10 oz/yd^2) material.

To have a closer look at a "wooley worm" failure, one of the affected fabrics was removed from the baghouse and dissected. The fabric chosen was one that had a vertical split along a fold line. In Photo 1, the inside portion of the fabric is shown just above the tear. From this photo the full extent of the massive fiber damage along these fold lines can be observed. Although the example shows only a single abraded area, it is not uncommon for two such areas to be very close to one another, suggesting that the fabric was actually folding back on itself and undergoing abrasion.

The deflation process is expected to play only a minor role in the development of the "wooley worm" type failure observed at Harrington since the deflation levels employed are very low (approximately 0.5 cm (0.2 in.) w.g.) and observation shows no discernible flexing of the material. In order to examine the effect of shaking on the fabric, one compartment of an EPA-sponsored pilot baghouse currently in operation at Harrington was rebagged with one new Criswell 449-I580 0.48 kg/m^2 (14 oz/yd^2) graphite/Teflon/silicone (G/T/S) coating) and one Criswell 442-57DC2 0.34 kg/m^2 (10 oz/yd^2) Teflon-coated). The other thimbles were left unbagged to allow for better observation. The effect of the shaking forces on these fabrics was then viewed by entering the compartment at both the upper and lower levels. The motions of the fabric were complex; however, it was clearly apparent that the shaking forces were responsible for causing folding and flexing along certain lines in the fabric.

The two fabrics appeared to have somewhat different reactions to the shaking forces. The 0.34 kg/m^2 (10-oz/yd^2), Teflon-coated material seemed to transmit the intensity of shake farther down the fabric than the 0.48-kg/ m^2 (14-oz/yd^2) material. By comparison, the heavier fabric reacted to the same shaking forces in a more sluggish and lethargic manner than the lighter material. The 0.34-kg/m^2 (10-oz/yd^2) Teflon-coated fabric appeared to have a very "live" reaction to shaking. The degree to which flexing occurred in the cloth was also different for the two fabrics. The relatively limp 14-oz. material appeared to be undergoing a more severe folding action while the rigid Teflon-coated fabric tended to resist the folding forces.

It is felt that this difference in reaction to the shaking forces may play the principal role in the premature failure of the 449 fabrics installed at Harrington Station. The more rigid Teflon coating may be protecting the fabric by mechanically restricting its motion during the cleaning cycle. The reaction of fabric to the forces employed during cleaning is undoubtedly one of the most important factors in determining fabric life. Further studies of this type are planned for the pilot unit in order to better define the reaction of various fabrics to shaking forces and its relation to fabric wear.

Reducing Fabric Wear

After an appreciation has been developed for the mechanisms involved in fabric wear, the next logical step is to attempt to minimize these actions by some means. One method of reducing the severity of the folding and flexing wear occurring during the shaking process that appears to hold promise is that of employing smaller shake amplitude by replacing the existing eccentric with one having less of a throw. The intention of such a change is that the fabric would undergo less severe flexing; however, if this is the only change made, cleaning will suffer as more dust cake will be left on the fabric. Dennis (2) has shown that dust removal is a linear function of the acceleration applied to a fabric. The acceleration, a, imparted to a fabric during shaking is proportional to Af^2 where A is the amplitude and f is the frequency. Dennis gives the equation

$$a = 4\pi^2 kAf^2 \qquad (1)$$

where $k \simeq 0.7$.

The ratio of acceleration compared to some standard values for A and f on a given system can be calculated from

$$\text{(acceleration ratio)} \qquad \frac{a}{a_s} = \frac{Af^2}{A_s f_s{}^2} = \frac{\gamma d^2}{\gamma_s d_s{}^2} \qquad (2)$$

where

d = sheave diameter
γ = eccentric throw

If, for example, the fabric was being shaken by a mechanism employing a 13.5-cm (5.3-in.) drive pulley and a 1.3-cm (1/2-in.) throw eccentric and a change of eccentric is accomplished to one with a 1 cm (3/8-in.) throw, then the acceleration would be only 75 percent of its former value.

A study was undertaken at Harrington to determine the impact of amplitude and frequency changes on cleaning by placing different sizes of eccentrics and shaker motor pulleys (sheaves) on several compartments and measuring the change in flow through the compartment with manometers installed across the outlet dampers.

The relative flow after cleaning vs. the acceleration ratio plot is shown in Figure 6. The plot confirms the results reported by Dennis in that a directly proportional measure of dust removal, through-put after cleaning, is linearly related to the acceleration imparted to the fabric during shaking.

From Figure 6 it is apparent, then, that reducing the eccentric throw from 1.3 cm (1/2-in.) to 1 cm (3/8-in.) would cause an unacceptable lowering of flow through a compartment if no other changes were made. However, as can also be seen from the plot, the installation of a 15.2-cm (6-in.) pulley brings the acceleration ratio back close to 1.0 and the flow comes back to the same level as under the original conditions. Therefore, increasing sheave size can be used in conjunction with smaller shake amplitudes without incurring unacceptable losses in cleaning. In light of this, studies are now underway to determine the effect on fabric wear of employing 1-cm (3/8-in.) eccentrics and 15.2-cm (6-in.) shaker motor pulleys instead of the 13.5-cm (5.3-in.) pulleys and 1.3-cm (1/2-in.) eccentrics currently being used.

CONCLUSION

The results of fabric filtration analyses are now beginning to reveal performance trends for various types of fabrics. In the coming months, SPS plans to look at dust and flow distribution by analyzing individual compartment pressure drop behavior. SPS hopes to make more compartment observations and conduct individual compartment through-put measurements. In addition, SPS will continue to evaluate different fabrics, including two entire compartments of 0.34 kg/m^2 (10 oz/yd^2) Acid Flex coated bags and one compartment of 0.19 kg/m^2 (5.5 oz/yd^2) Nomex bags. As results of these studies become available, SPS looks forward to sharing them with other utilities considering fabric selection in association with coal-fired boilers.

ENDNOTES

1. Chambers, R. C., Ladd, K. L., and Kunka, S. L., "SPS Experience With Fabric Filtration," presented at 5th International Fabric Filter Forum, Phoenix, Arizona, January 1981.

2. Dennis, R.C., Cass, R.W., Cooper, D.W., Hall, R.R., Hampl, V., Klemm, H.A., Langley, J.E., and Stern, R.W., GCA Corporation. "Filtration Model for Coal Fly Ash With Glass Fabrics," EPA-600/7-77-084 (NTIS No. PB 276 489), August 1977.

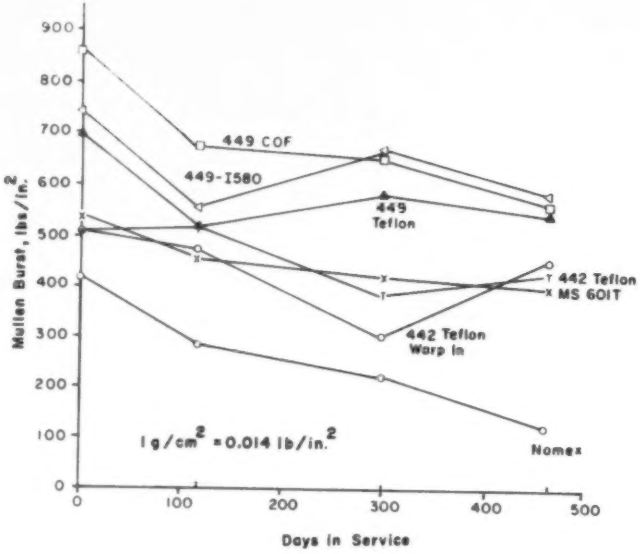


Figure 1. Mullen Burst

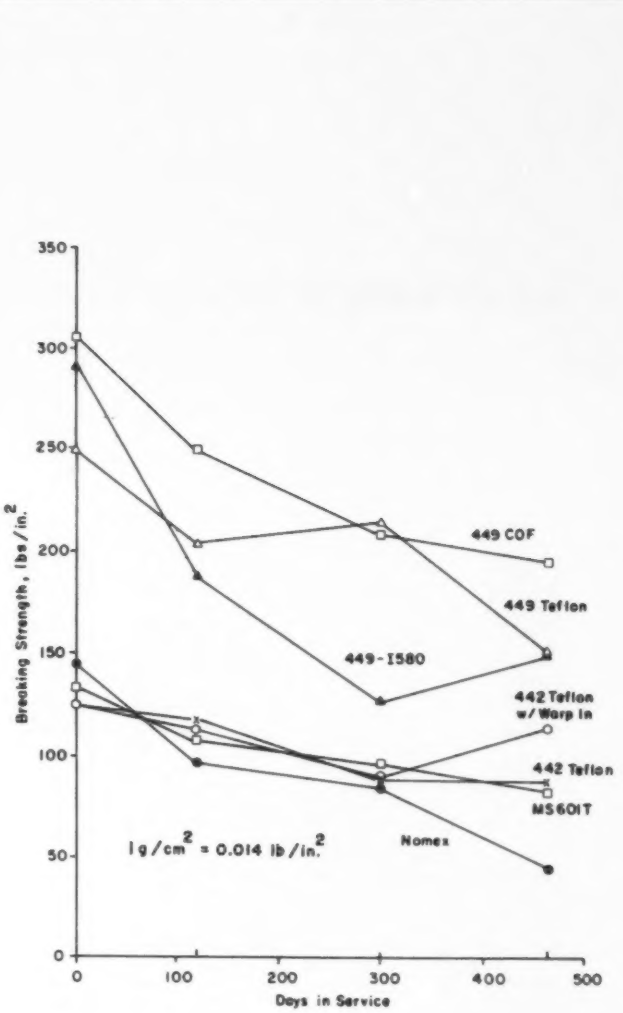


Figure 2. Breaking Strength

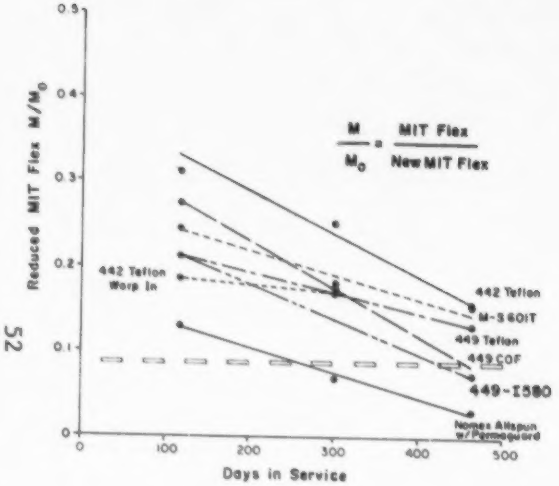


Figure 3. Reduced MIT Flex vs. Time

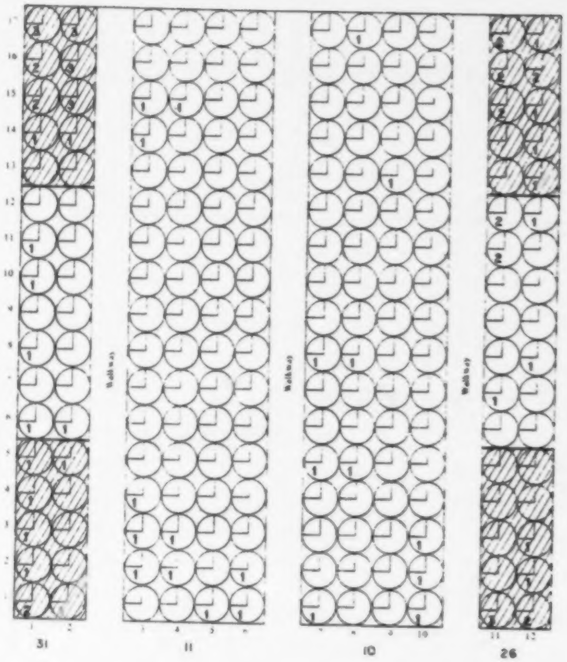
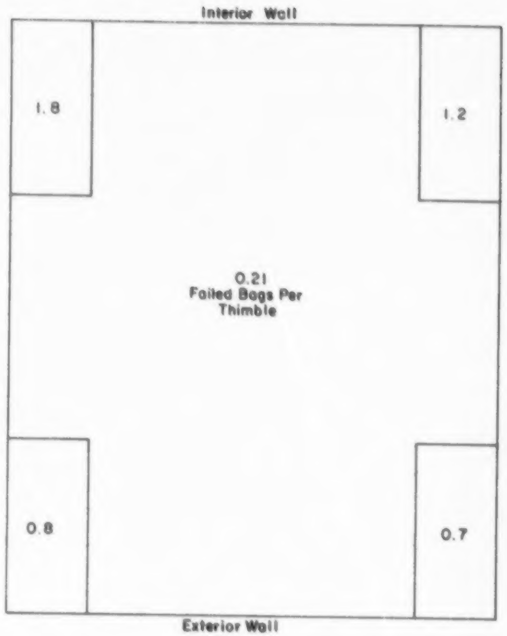

Walkway
Walkway
Walkway
31
11
10
26

Figure 4. Failures by Thimble Position


Interior Wall
1.8
1.2
0.21
Failed Bags Per
Thimble
0.8
0.7
Exterior Wall

Overall Average = 0.39 Failures by Thimble

Figure 5. Failure by Compartment Position

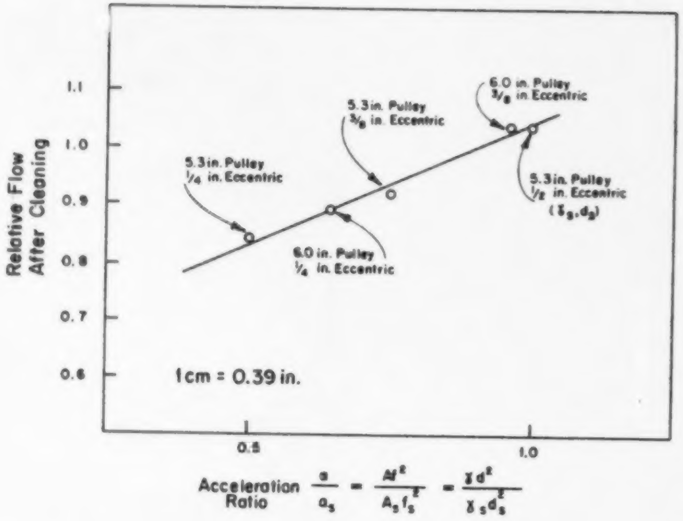


Figure 6. Effects of Various Sheave And Eccentric Sizes on Cleaning

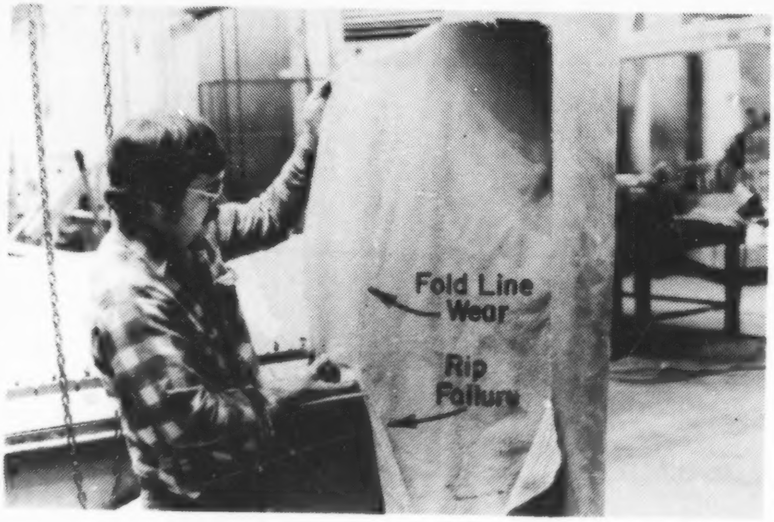

Fold Line Wear
Rip Failure

Photo 1. Dissection of "Wooley Worm" Failure

SPS PILOT BAGHOUSE OPERATION

By: Kenneth Ladd, Wanda Hooks, and Sherry Kunka
Southwestern Public Service Company
P. O. Box 1261
Amarillo, Texas 79170

Dale Harmon
Industrial Environmental Research Laboratory
Environmental Protection Agency
Research Triangle Park, North Carolina 27711

ABSTRACT

In 1977, the Environmental Protection Agency (EPA) executed a contract with Southwestern Public Service Company (SPS) to assess the performance of a large fabric filter system used on a new utility boiler burning low sulfur Western coal. One option of this contract provided for the installation of a pilot filter system on-stream with Harrington Station Unit 2. This paper outlines the overall objectives of the pilot unit program. In addition, proper system design, problems in start-up and operation, and a fabric evaluation program are discussed.

INTRODUCTION

Southwestern Public Service Company's fabric filter study contract (EPA No. 68-02-2659) with the EPA included a provision to exercise an option for a pilot baghouse. In 1980, the EPA elected to exercise this option. Southwestern agreed to operate and maintain a pilot unit at Harrington Station in conjunction with Unit 2 for a 3-year period.

The objectives of this option are (1) to operate the slipstream unit under the same operating parameters as the full-scale unit, and (2) to develop scale-up parameters from the slipstream unit to the large operation. Additionally, optimization of operating techniques will be determined on the pilot baghouse and applied to the full-scale unit. Another phase of the pilot project is to conduct detailed studies on fabric performance. Individual fabrics will be examined to assess the performance of bags with different coatings. The cleaning effect of various weaves and of different sizing removal procedures (chemical cleaning, heat cleaning, coronizing) will also be studied.

Description

The pilot unit is a Wheelabrator-Frye, Inc., Model 366, Series 11.5 RS Dustube Dust Collector. It has two 6-bag compartments and initially was fitted with Criswell Style 442 10 percent Teflon-coated fabric. The bags were 29.2 cm (11.5 in.) in diameter and 930 cm (366 in.) long, untensioned. Cloth area per compartment is 51 m^2 (549 ft^2)

The unit is operated by a 480-V control panel and an instrumentation panel. The 480-V control panel houses the damper controls, hopper heater controls, cleaning cycle timers, fan start/stop controls, and bypass automatic controls. The instrumentation panel houses ΔP, flow, and temperature monitoring devices as noted in Table 1.

TABLE 1. INSTRUMENTATION PANEL

△P west recorder
Flow west recorder
Outlet temp recorder
West compartment flow
Inlet temp--temp control
Dampers

△P east recorder
Flow east recorder
Inlet temp recorder
East compartment flow
Off preheater, hot and cold

Installation

The installation of the pilot baghouse began when the modules arrived on the job site around June 1, 1979. The pilot is installed at the southeast corner of the east baghouse on Harrington's Unit 2. The inlet flue gas to the pilot is pulled from the east inlet duct of the main baghouse and mixed with the hot preheater flue gas with a mixing valve to maintain temperature. (See Figure 1, Pilot Baghouse Schematic.)

The actual installation consists of the following:

Piping

41 cm (16-in.) I.D.	Elbow from preheater prior to reduction
30 cm (12-in.) I.D.	From preheater
20 cm (8-in.) O.D.	Bypass
36 cm (14-in.) I.D.	To east and west inlet before branch
20 cm (8-in.) O.D.	To east and west inlet after branch
41 cm (16-in.) I.D.	From main baghouse inlet duct
15 cm (6-in.) O.D.	Recirculation
36 cm (14-in.) I.D.	From pilot outlet plenum to main fan
36 cm (14-in.) I.D.	Crossover from main fan
41 cm (16-in.) I.D.	From main fan crossover to main baghouse duct

Motors

Deflation	7.5 kW (10 H.P.)	3600 rpm	Siemens - Allis, Inc.
Main fan	37.3 kW (50 H.P.)	3600 rpm	Siemens - Allis, Inc.
Shaker	0.75 kW (1 H.P.)	900 rpm	3/60/230/460 Siemens - Allis, Inc.
Variable-speed shaker	3.75 kW (5 H.P.)	1710 rpm	Reliance

Dampers

30 cm (12-in.)	Outlet - Poppet
15 cm (6-in.)	Deflation - Butterfly
20 cm (8-in.)	Bypass - Butterfly
10 cm (4-in.)	Recirculaton-Manual Operation - Recirc. Deflation Dust Air - Butterfly

Fans

Deflation	222-4-15 PBF Thermal-aire Design Garden City Fan Co.
Main	15RF2 Thermal-aire Design Garden City Fan Co.

SCOPE OF WORK

The pilot unit is designed to be used over a 3-year period for a series of research activities. Certain "technical directives," or tasks, have been set out in the contract for the pilot study. When these tasks are accomplished, they will be written up as task reports and published as individual publications under EPA cover.

SPS and the EPA discussed several areas of potential testing and developed a list of tasks which reflected the interest of both parties. These study areas include:

Filtration parameters - Average $\overline{K_2C}$ and ΔP_E daily so that these parameters may be studied versus air-to-cloth ratio.

Particulate Tests - Inlet/outlet grain loading and particulate size distribution to determine fabric efficiency, size distribution, and comparison of grain loadings to main unit.

Modeling Parameter - Find K_2, ΔP_E as a function of V by varying air-to-cloth ratio, to be used in developing a filtration empirical model.

Extended Filtration Time - To determine the effect of extending filtration time on system pressure drop (clean better but less often).

Scale-up - Develop scale-up equations from a pilot unit to a multi-compartment fabric filter system.

Reverse Air Cleaning - Information will also be used to develop modeling parameters for reverse air cleaning.

Fabric Testing - Evaluate fabrics not already under test and exotic fabrics too expensive for full-compartment assessment.

Future Studies - Investigate potential of extending studies to higher grain loadings and utilizing other fly ashes because of variability of coal supplies to other utilities.

Start-up Plan

Prior to the actual start-up, a preliminary equipment checkout was conducted. The 480-V control panel was energized with all valves from flue gas sources closed. Hopper heaters were set at 132°C (270°F) and allowed to heat for 16 hours prior to start-up. With all controllers in the closed position, the outside dampers were manually opened and the following steps taken.

1. Open damper from preheater.
2. Open flue gas inlet damper.
3. Open return damper.
4. Open inlet damper to main fan.
5. Open bypass butterfly valve.
6. Close bypass valve.
7. Open outlet dampers.
8. Start main fan.
9. Activate east and west flow controllers.
10. Activate temperature controller.
11. Start deflation fan.
12. Set cleaning cycle to automatic.

The inlet temperature was controlled automatically at 232°C (450°F) for the first 24 hours, at which time it was decreased to 204°C (400°F). The inlet flow was 935 m^3/h (550 acfm) for 2 hours at an air-to-cloth ratio of 1. At the end of the 2-hour period, the air-to-cloth ratio was increased, but not to exceed 2 for the first 24 hours.

The cleaning cycle was not to be activated until the ΔP reached 13 cm (5 in.) w.g. At 13 cm (5 in.) w.g., the cleaning cycle was set up on a 20-sec shake. Each compartment was to clean on a 33-min cycle, 25-sec settle, and 35-sec final settle. Ash was to be manually removed once a day, one hopper at a time, until automatic mode modifications could be made.

OPERATION

The pilot baghouse was first placed in service on October 23, 1979; however, painting, insulating, guard rail installation, and construction cleanup continued for about 8 weeks. On initial start-up, excessive condensation was present. Therefore, to prevent moisture condensation on future start-ups, the manual inlet from the air preheater was opened to allow compartments to heat.

Prior to the annual Harrington Unit 2 outage, numerous problems were encountered. Immediate problems after start-up were (a) high temperature loss; (b) constant tripping of the variable speed shaker motor; (c) improper wiring; (d) inadequate bracing of the inner compartment wall; and (e) in-leakage. These problems were minor and were resolved shortly after start-up.

The biggest problem, in-leakage, was believed to be due to warped doors, all four of which it was decided to replace. By the end of November 1979 the new doors had arrived; installation was completed in 4 days. Ultrasonic leak testing was performed by SPS and WFI engineers and small leaks in the back wall were repaired.

Modifications and Problems

During the 1979 fall outage (October 26-December 10) the following pilot modifications were made for ease of operation:

1. Made ash system automatic with main unit.
2. Installed compartment isolation switches.
3. Relocated cleaning cycle timers to enclosure on back of 480-V breaker for ease of access.

After the annual outage, the pilot was again started up on January 3, 1980. Start-up followed the standard procedure established for the initial start-up with 1700 m^3/m (1000 acfm), 232°C (450°F) on inlet, and automatic cleaning at 33-min intervals. After 4 days, the air-to-cloth ratio was decreased to 2 to see if lower flow would increase the temperature loss. The temperature loss, however, held stable at 43°-46°C (110°-115°F). During the following few days the instrument shop confirmed that both inlet and outlet thermocouples were performing accurately.

By mid-January, it was obvious that the temperature loss due to possible air leakage was going to have to be dealt with. Faulty outlet damper packings were found to be pulling air in directly on top of the outlet thermocouple. Both sides were packed and have worked well ever since.

The temperature loss problem still had not been completely solved, however. A new temperature tap was put in the outlet plenum to see if the outlet thermocouple and the one in the plenum read the same; they did. At this time temperature probes were placed in manometer taps at the cell plate level to see if temperature loss was uniform throughout each compartment: some evidence pointed to ash hopper or below the cell plate in-leakage. A check of the in-leakage ash through the hopper dump gates failed to reveal significant in-leakage.

In February, SPS began a series of four O_2 tests, performed by the SPS environmental test group. These tests still pointed to high in-leakage with the temperature loss at a 3.4 air-to-cloth ratio at 17°C (63°F). Eventually, a faulty fabrication weld in the west ash hopper was discovered. The joint had been tack-welded and never seal-welded. This was promptly repaired.

In April 1980, leaks were repaired in the roof at the wall joint in both the east and west compartments. In addition, leakage was repaired below the cell plate on the east side. By mid-April, O_2 testing had shown that in-leakage was at an acceptable level. The pilot unit was scheduled for official start-up, and the doors were sealed with silicone to prevent future in-leakage.

By May 5, 1980, the pilot unit was on line and was operating satisfactorily. The most recent in-leakage test proved acceptable: it showed a temperature loss of only 8°C (47°F) at an air-to-cloth ratio of 3.4.

Special Testing

For 4 days in mid-July 1980, the SPS environmental test group tested the pilot baghouse to measure particulate and gaseous emissions. Test procedures were those specified for EPA Methods 1, 2, 3, 4, and 5 (40 CFR 60, Appendix A). Results are shown in Table 2.

This limited amount of testing indicates that flue gas constituents for the pilot baghouse are equivalent to those of the main baghouse. For instance, an average inlet particulate concentration of 4.6 (±0.7) g/m^3 (2.0 (±0.3) gr/scf) for the pilot baghouse is comparable to 3.9 (±0.9) g/m^3 (1.7 (±0.4) gr/scf) for the main baghouse. (Note that averages for the pilot baghouse are based on three samples, and averages for the main baghouse are based on 21 samples.) On the pilot baghouse outlet side, an

TABLE 2. PARTICULATE TEST SUMMARY

	Inlet			Outlet		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Orsat Gas Analysis, %						
CO_2	13.7	13.9	14.8	13.0	13.4	13.4
CO	0.0	0.0	0.0	0.0	0.0	0.0
O_2	5.7	5.5	5.3	6.5	6.1	6.0
N_2	80.6	80.7	80.5	80.5	80.5	80.6
Particulate Results						
% Moisture	11.3	11.3	11.1	11.1	11.0	10.5
Wet Stack Gas Mol. Wt.	29.0	29.0	29.1	29.0	29.0	29.1
Particulate Concentration g/m^3	5.5	4.4	3.9			
(gr/scf)	(2.4)	(1.9)	(1.7)	0.0	0.0	0.0
Isokinetic Variation, %	97.9	96.7	96.9	101.8	101.7	99.5

average particulate emission rate of 1.3(±0.4)ng/J(0.003 (±0.001) lb/10^6 Btu) compares to an average particulate emission rate of 13(±4)ng/J (0.03 (±0.01) lb/10^6 Btu) for the main baghouse (pilot baghouse averages are based on 3 samples and main baghouse averages based on 10 samples).

Similar tests in the future will determine the value of using pilot flue gas testing results as scale-up factors to the main baghouse to compare fabric efficiency, size distribution, and grain loadings. Factors such as the length of time bags have been in service and pressure drop, however, may also be needed before drawing conclusions about baghouse performance based on data from the pilot unit.

Data Collection

Official data on the Criswell 442-57DC2 bags was collected from May through September 1980. This data was collected at air-to-cloth ratios of 1.94, 2.20, 2.50, 2.80, and 3.40. (See Table 3, Data Collection Averages.) Each average in this table represents 48 cleaning cycles with 96 data points each.

To determine the specific resistance coefficient (K_2), the pressure drop across the bags at both the beginning ($\triangle P_E$) and the end ($\triangle P_T$) of the cleaning cycle must be known. The pressure drop is recorded on a paper chart recorder. To obtain numbers for calculating $\triangle P_E$ and K_2, the strip chart must be unrolled, the cleaning cycles measured, and a line drawn through the linear part of the graph. $\triangle P_E$ is measured by an extrapolation of this line. Values for $\triangle P_E$ and $\triangle P_T$ are then used to calculate an average value for K_2C with the aid of a programmable calculator.

The cleaning cycle is about 30 minutes long, and there are two compartments to be calculated. This means that for every 15 minutes, this process must be performed. It takes approximately 60 man-hours per month to obtain values for K_2 and $\triangle P_E$ by this method (2,880 cleaning cycles per 30-day period, 5,760 points to read $\triangle P_E$ and $\triangle P_T$ for each 30-day cleaning cycle, 28,800 points per data chart).

Reverse Air Experiments

During the Unit 2 1980 fall outage (October 3-November 8), plans were made for a reverse air experiment on the west side of the pilot baghouse. By October 23, 1980, the Criswell 442-57DC2 bags had been removed. The east compartment was fitted with six used Nomex bags and the west with six new ringed Kennecott 0.28 g (10 oz) bags. In order to avoid ash carryover from one compartment to the other during cleaning, the Nomex compartment employed shake cleaning only, while the test compartment used reverse air cleaning.

For the reverse air experiment, the cleaning cycle timers were set as follows:

First settle - 30 sec.
Reverse air - 45 sec.
Second settle - 30 sec.
45-min intervals for 3 days.
60-min intervals for duration of test.

The reverse air start-up followed standard procedure (204°C (400°F) inlet temperature, air-to-cloth ratio 2.0). Performance of the pilot unit during the reverse air mode was satisfactory with only minor mechanical

TABLE 3. DATA COLLECTION AVERAGES

EAST

Air-to-Cloth Ratio	May ΔP_E	May ΔP_T	June ΔP_E	June ΔP_T	July ΔP_E	July ΔP_T	August ΔP_E	August ΔP_T	September ΔP_E	September ΔP_T
1.94					2.65	2.97	3.09	3.44	3.60	3.89
2.20					3.36	3.68				
2.50									4.66	5.13
2.80			4.62	5.39	4.67	5.39				
3.40	5.93	7.34	5.12	6.45	6.17	7.64	6.93	8.25	6.38	7.62

WEST

Air-to-Cloth Ratio	May ΔP_E	May ΔP_T	June ΔP_E	June ΔP_T	July ΔP_E	July ΔP_T	August ΔP_E	August ΔP_T	September ΔP_E	September ΔP_T
1.94					3.14	3.43	3.32	3.64	2.98	3.29
2.20					3.59	4.03				
2.50									4.03	4.46
2.80			4.44	5.12	4.65	5.39				
3.40	4.93	6.41	4.74	5.89	5.74	7.12	6.20	7.36	6.40	7.61

Criswell 442-57DC2 Fabric
Inlet Temperature 204°C (400°F)
Cleaning Interval - 33 minutes, 20-second shake
Each average represents 48 cleaning cycles, 96 data points.

$K_2 = 15\text{-}28 \ \frac{\text{in. w.g. min. ft.}}{\text{lb}_m}$

ΔP_E is pressure drop across bags at beginning of cleaning cycle.
ΔP_T is pressure drop across bags at end of cleaning cycle.
Averages reported in in. w.g. (1 cm = 0.39 in.).

problems, if the Nomex fabric was cleaned every hour without deflation. The Kennecott fabric averaged a residual ΔP of 16.0 cm (6.31 in. w.g.); a terminal ΔP of 19.8 cm (7.78 in. w.g.) for a 60-min cleaning cycle at an air-to-cloth ratio of 2.3; and an inlet temperature of 204°C (400°F), during the 14-day test.

On December 31, 1980, the pilot was taken off line for installation of the second test fabric (Fabric Filters 502-1 Acid Flex). To obtain faster break-in, cleaning was set at automatic 30-min. intervals regardless of pressure drop. Following the break-in period, the cleaning cycle was set to 60-min and the test extended to 3 weeks.

The SPS reverse air testing program will run through July 1981. SPS plans to run 11 tests during this time, involving various fabric finishes and numbers of rings in the bag. Table 4 shows the fabrics to be evaluated.

TABLE 4. PILOT BAGHOUSE TEST FABRIC SELECTION

	Bag Type	Bag Weight g (oz)	Supplier
1.	Kennecott	0.28 (10)	Kennecott
2.	502-1 Acid Flex (Burlington I625)	0.40 (14)	Fabric Filters
3.	Q78-877	0.40 (14)	Globe-Albany
4.	449-COF(Heat cleaned)	0.40 (14)	W. W. Criswell
5.	Fabric Filters 504-1 Tex Flex	0.28 (10)	W. W. Criswell
6.	Fabric Filters 504-1 Tuff Coat	0.28 (10)	W. W. Criswell
7.	502-1 Tuff Coat (Burlington)	0.40 (14)	Fabric Filters
8.	601 Tuflex	0.28 (10)	Menardi Southern
9.	Best candidate from previous with seven rings.		
10.	Same as Item 9, except five rings.		
11.	Same as Item 9, except nine rings, if time allows.		

ENDNOTES

1. Chambers, R. C., Ladd, K. L., and Kunka, S. L., "SPS Experience With Fabric Filtration" presented at 5th International Fabric Filter Forum, Phoenix, Arizona, January 1981.

2. Dennis, R. C., Cass, R. W., Cooper, D. W., Hall, and Stern, R. W. GCA Corporation. "Filtration Model for Coal Fly Ash With Glass Fabrics, "EPA-600/7-77-084 (NTIS No. PB 276 489), August 1977.

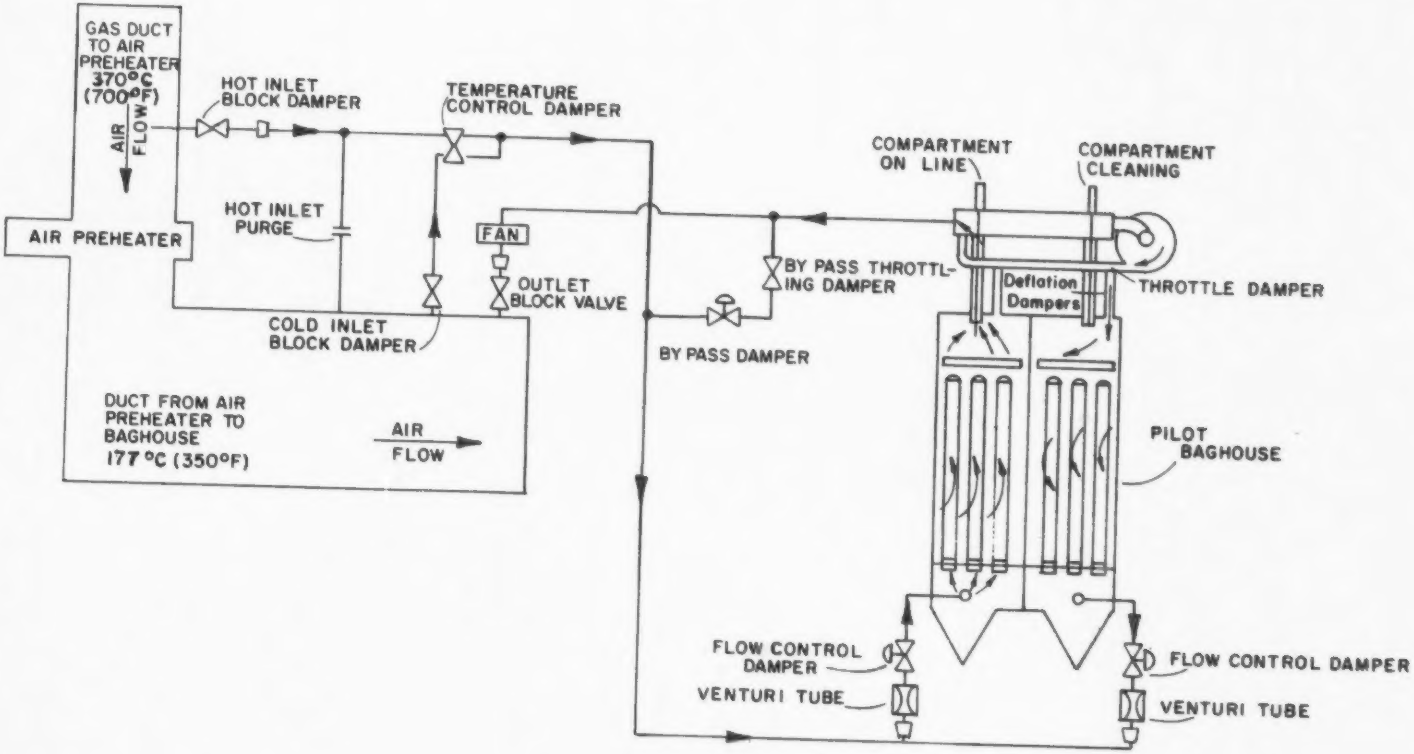

GAS DUCT TO AIR PREHEATER 370°C (700°F)
AIR FLOW
HOT INLET BLOCK DAMPER
TEMPERATURE CONTROL DAMPER
COMPARTMENT ON LINE
COMPARTMENT CLEANING
AIR PREHEATER
HOT INLET PURGE
FAN
OUTLET BLOCK VALVE
BY PASS THROTTLING DAMPER
Deflation Dampers
THROTTLE DAMPER
COLD INLET BLOCK DAMPER
BY PASS DAMPER
DUCT FROM AIR PREHEATER TO BAGHOUSE 177°C (350°F)
AIR FLOW
PILOT BAGHOUSE
FLOW CONTROL DAMPER
VENTURI TUBE
FLOW CONTROL DAMPER
VENTURI TUBE

Figure 1. Pilot Baghouse Schematic

REVIEW OF SPS INVESTIGATION OF HARRINGTON STATION UNIT 2 FABRIC FILTER SYSTEM

By: Kenneth Ladd and Sherry Kunka
Southwestern Public Service Company
P. O. Box 1261
Amarillo, Texas 79170

ABSTRACT

For the last three years, Southwestern Public Service Company (SPS) has tested and monitored the Harrington Station Unit 2 fabric filter system in an effort to characterize its operation. This fabric filter system was one of the first large air quality control devices to be used in association with a low-sulfur, coal-fired boiler. Start-up, monitoring, testing, and operation of the fabric filter system since an EPA-sponsored program began in October, 1977 are discussed in this paper.

In addition, the operation and maintenance problems encountered during the first year of the program are reviewed. A summary of the extensive flue gas and particulate sampling performed by SPS and its subcontractor, GCA Corporation, is presented. A brief discussion of fabric problems encountered during the last three years is also included.

INTRODUCTION

Background

Southwestern Public Service Company (SPS), an electric utility with headquarters in Amarillo, Texas, undertook a project with the Environmental Protection Agency (EPA) in 1977 to assess a new application for fabric filter technology. The site selected for the study was Harrington Station, SPS's first coal-fired generating plant. In 1978 when it was put on-line, Harrington's Unit No. 2 was the first new utility boiler to be equipped with a fabric filter system (baghouse) for particulate control. Its effectiveness in controlling emissions from a coal-fired boiler was of special interest to the EPA in its effort to set standards for air quality control equipment.

The objectives established for the study are described below. These objectives were formulated to help utilities and other coal-burning facilities obtain information for evaluating air control alternatives. SPS especially hopes to aid those burning low-sulfur Western coal.

1. Determine operating and maintenance costs of an operating fabric filter system over an extended period of time in order to give other utilities data on the economic feasibility of baghouses.
2. Characterize performance of the unit by looking at specific parameters which include (a) an assessment of the effect of pressure drop versus time; (b) removal efficiency to be determined by special manual testing; (c) continuous opacity monitor-

ing; (d) an investigation of the long-term reliability of the systems; and (e) determination of optimum operating conditions.

3. Bag performance and bag life will be studied by (a) periodic removal of test bags for analysis by an independent consultant; (b) analysis of pressure drop and thru-put on an individual compartment basis; and (c) other special fabric studies.

The study is now in its fourth year. The remaining project time will be spent analyzing continuous monitoring data and assessing the cost of operation and maintenance activities. Project activities during the first two years of study are discussed in the first and second annual reports (1, 2).

Facility Description

Harrington Station, SPS's first coal-fired plant, is located approximately five miles northeast of Amarillo, Texas. The first 360 MW unit went into operation July, 1976; a second 360 MW unit went on-line in 1978 and Unit 3 was brought into service in 1980.

The particulate emission control device selected for Unit 2 is a Wheelabrator-Frye, Inc. (WFI) fabric filter baghouse system. It is designed to operate at a flue gas flow of 1,650,000 acfm at 313°F. Minimum design efficiency is 98.6 percent, which would permit 0.1 pounds of particulate per million BTU out the stack. The exterior of the baghouse has 3.5 inches of fiberglass insulation; there is no insulation between plenums and compartments. Other design parameters are summarized in Table I.

Table I. Fabric Filter System Design Parameters

Compartments	28
Bags per compartment	204
Bag diameter	11.5 inches
Bag length	30.5 feet
Bag spacing, center to center	14.0 inches
Air-to-cloth ratio, gross	3.16:1
Air-to-cloth ratio, net	3.40:1
Bag reach	2

Start-up

SPS formulated a start-up procedure for the Harrington Station fabric filter system after reviewing start-up experience of other utilities and after consulting individuals known to have experience in start-up of these systems. A set of guidelines was written for the actual start-up and these were described in an earlier paper devoted to start-up of the fabric filter system (3).

No start-up difficulties were experienced. Problems associated with the acid dewpoint had been of concern but neither bag blinding or corrosion due to excessive moisture was noted. As the final bypass damper closed, the opacity dropped to one percent. This drop was signalled dramatically by the perfectly clear stack.

Approximately three weeks after the baghouse was initially started, SPS was able to operate Unit 2 at full load with only coal in service. Since that time, the unit has operated at loads consistently above 200 MW and during peak periods, loads over 350 MW.

OPERATING AND MAINTENANCE EXPERIENCE

The fabric filter system has functioned very well in terms of overall performance. Consistent stack opacity monitor readings in the two to four percent range indicate that the baghouse is doing an excellent clean-up job. Specific areas of operating and maintenance experience are discussed below. Despite the favorable removal efficiency of flyash from the low sulfur coal, some major concerns arose. The first major difficulites to be encountered were high pressure drop and problems with cleaning the bags. Later, fabric wear and performance resulted in a need for evaluation and change.

Deflation

Unit 2 started up and operated until mid-June, 1979 without good deflation control. WFI recommended that deflation levels be at 0.5 inches w.g., which was very difficult to maintain manually.

During this period of time, SPS ran tests to see if bags were pancaking at 0.5 inches w.g. deflation pressure; results indicated that severe pancaking was taking place. By watching bags through observation ports in one compartment and lowering the deflation pressure drop until pancaking no longer occurred, 0.1 to 0.2 of an inch w.g. deflation pressure was determined to be an appropriate level to prevent pancaking. A control unit was installed by WFI, which gave operators the capability to change deflation from the control room, enhancing the ability to keep deflation at indicated levels.

Shake

Correction of deflation improved baghouse operation, but it was apparent that the bags still were not being adequately cleaned. More force was needed to release the fly ash from the cloth. To determine the effect of increased acceleration on cleaning, SPS decided to run some experimental tests with 6-inch shaker pulleys in place of the 4-inch diameter pulleys originally provided. Modifying the amplitude of the shaker to increase fabric acceleration during cleaning would have required fabrication of a special eccentric. Shaker frequency, however, is modified simply by changing the main drive pulley on the shaker motor shaft.

Table II shows a summary of compartment pressure drop comparisons for the 4-inch and 6-inch diameter shaker pulleys.

Table II. Summary of Compartment ΔP Comparisons*

Compartment	ΔP	Difference	Compartment	ΔP	Difference
17	9.75	0.45 (4-inch)	17	10.37	0.00 (4-inch)
21	8.30	1.45 (4-inch)	21	7.13	3.24 (6-inch)
23	8.65	1.10 (4-inch)	23	7.33	3.04 (6-inch)

* @ 350 mw.

It appeared that the increased shake doubled or tripled the decrease in pressure drop. As a result of the experimental work with 6-inch diameter shaker pulleys, SPS decided to replace all of the 4-inch pulleys with 5.3-inch pulleys in all of the compartments.

Adjustment to Shaker Mechanisms

Increased shaker frequency (or rapidity) resulted in problems with the existing pillow blocks. The original structure simply had pillow blocks bolted to a plate without any lateral support and at least a quarter inch of shims was used to properly locate the pillow block. After installation of 6-inch pulleys on shaker mechanisms, the higher forces caused movement of pillow blocks and eventual damage to shaker mechanisms.

To remedy the situation, SPS designed a modified pillow block support structure. Since this modification was made in August, 1979, no failures have been observed due to loose pillow blocks.

Ventilation System

The design of the Harrington Station Unit 2 baghouse leaves the inside compartment and duct walls uninsulated in order to allow the compartments to be heated while the flue gas bypasses the baghouse. This design prevents condensation and corrosion problems during start-up. Single compartment inspections can be performed with the unit on-line as long as it is not necessary for personnel to enter the upper level of the compartment. Since replacement of blown-out bags requires upper level entry where temperatures may be greater than 130°, a ventilation system became necessary for each compartment.

The ventilation system consists of a single fan on the ground level in duct work to and dampers for each of the 28 compartments. The system has been sized to deliver approximately 60,000 cfm of ambient air for compartment cooling.

Replacement of Hopper Heaters

Original hopper heaters in the Unit 2 fabric filter system were made of silicone rubber and applied with an adhesive to the hopper shell. During the first year of operation, 99 percent of these heaters failed. Beginning in September of 1979, they were replaced with a modular box-style heater.

Safety Features

During a Unit 2 outage in April of 1979, safety devices to prevent doors from blowing shut were placed on all compartment doors. Seals on all compartment doors were also replaced on an as-needed basis during the second year of study.

Opacity

The Lear-Siegler RM41 Opacity Monitor appears to be a very stable and dependable instrument. To date, the device has needed very few adjustments and has had few maintenance problems. The sensitivity of the unit has allowed it to be used in precise pinpointing of failed bags by compartment.

In order to get good measurements, however, it is necessary to do a clear stack alignment while the unit is off-line, i.e., during an overhaul. All attempts to do bench alignments have proven unsatisfactory.

SPECIAL TESTING

One of the major aims of the SPS/EPA study is to determine mass emissions of particulate, sulfur dioxides, and oxides of nitrogen. The contract specifies a special testing program designed to measure these parameters and relate results to the collection efficiency of the fabric filter system.

The original work plan called for three special tests by SPS. However, the test dates were altered in order to allow for changes in operating conditions and budget limitations. Tests were conducted by SPS at the following times :

Phase I	December 11-15, 1978
Phase II	October 8-12, 1979
Phase III	March 24-25, 1980
Phase IV	August 26-29, 1980

The contract also called for three more specialized tests to be conducted by an outside consultant under subcontract to SPS. GCA Corporation was selected to sample at five locations for the following parameters: particulate, C_7-C_{17} organic compounds, C_1-C_{16} organic compounds, CO_2, O_2, CO, SO_2, SO_3, NO_x, and particulate particle size distribution.

GCA conducted their first test in February, 1979. Results from this test led SPS and the EPA to a decision to reduce this phase of the test program to only one more test to be performed as a joint test by SPS and GCA. Furthermore, the test parameters were reduced to the following: particle size distribution by three methods and SO_2 and SO_3 sampling at three locations. This series of tests was performed in June, 1980.

Procedures followed during periods of special testing were implemented by the Environmental Group of the SPS System Laboratory for collection, recovery, and analysis of samples for the determination of particulate, SO_2, NO_x, and combustion gases (O_2 and CO_2) in flue gases during special test periods. In addition, the System Lab fabricated certain pieces of test equipment, followed standard calibrating procedures, and employed quality control/quality assurance policies. The procedures for the special test program were basically the same as EPA Methods 3, 5, 6, and 7 as outlined in the Federal Register (40 CFR 60, Appendix A).

A crew of test personnel from SPS power plants was assembled at Harrington Station for the first week-long series of tests. Approximately 26 stack sampling team members participated in the test program. By taking samples at three locations rather than five, experienced personnel were able to work with the less experienced ones. As a result, personnel at all the sampling locations had some degree of experience during the remaining tests.

Analyses of the special testing program are shown in Tables III, IV, V, and VI. The fundamental conclusion to be drawn from these results confirms that Unit 2 can operate in compliance with the New Source Performance Standard of 0.1 lb/10^6 BTU. The special testing phase of the SPS/EPA study has been completed. A report which deals exclusively with this portion of the program is currently being prepared.

FABRIC EXPERIENCE

The Unit 2 fabric filter system was originally equipped with bags of fiberglass with a silicone/graphite coating (W.W. Criswell Style 445-04).

Table III. Results of Particulate Testing

Phase I, December 1978

Run No.	East Inlet gr/scf	West Inlet gr/scf	Theoretical[3] Inlet gr/scf	Stack[4] gr/scf	Stack[4] lb/10^6Btu
1[1]	2.28	2.74	2.09	.053	.106
2[1]	2.04	2.56	1.96	.050	.097
3[2]	1.67	1.63	2.27	.033	.061

Phase II, October 1979

Run No.	East Inlet gr/scf	West Inlet gr/scf	Theoretical[6] gr/scf	East Outlet gr/scf	West Outlet gr/scf	Stack gr/scf	Stack lb/10^6Btu
1	1.40	1.41	1.79	.014	.012	.010	.020
2	1.61	1.41	1.78	.014	.024	.011	.021
3	1.61	.74[5]	1.81	.027	.028	.011	.022

Phase III, March 1980

1	[7]	[7]	1.82	.008	.012	.009	.017[8]
2	1.43	1.35	1.95	.013	.038	.013	.024
3	.97	1.14	2.03	.011	.022	.018	.032
4	[7]	1.50	2.04	.007	.020	.024	.044[9]

Phase IV, August 1980

Run No.	East Inlet gr/scf	West Inlet gr/scf	Theoretical[10] gr/scf	Stack gr/scf	Stack lb/10^6Btu
1	1.64	1.92	1.99	.016	.031
2	1.88	1.67	1.97	.009	.018
3	1.35	1.44	1.96	.015	.030

NOTES

[1] Sootblowing continuously.

[2] Not sootblowing.

[3] Assumes 70% fly ash, no consideration for sootblowing.

[4] The concentrations of particulate obtained from the stack are biased high because of a reaction that took place in the unheated Inconel probe liner.

[5] One sample of probe wash was lost during transport from sample site to the lab, causing this sample to be biased low.

[6] Based upon stoichiometric flue gas flow, coal flow, ash analysis; 70% fly ash generation; and 30% bottom ash and economizer ash generation.

[7] No data.

[8] Not isokinetic.

[9] Failed leak check test.

[10] Based upon stoichiometric flue gas flow, coal flow, coal analysis and 70% fly ash generation (dry basis).

Table IV. Results of NO_x Testing

Phase I, December 1978[1/]

Run No.	East Inlet Method 7	East Outlet Method 7	West Inlet Method 7	West Outlet Method 7	Stack Method 7
1	.68	.64	.61	.62	.63
2	.71	.68	.59	.62	.66
3	.67	.71	.62	.62	.64

NOTES

[1/] NO_x sampling was only performed one time.

Table V. Results of SO_2 Testing

Phase I, December 1978

Run No.	East Inlet[1] Method 6-lb/10^6Btu	West Inlet[1] Method 6-lb/10^6Btu	Stoichiometric[2] lb/10^6Btu	Stack Method 6-lb/10^6Btu
1	.53	.36	.76	.73
2	.59	.32	.84	.78
3	.62	.20	.88	.84

Phase II, October 1979

Run No.	East Inlet lb/10^6Btu	West Inlet lb/10^6Btu	Theoretical lb/10^6Btu	East Outlet lb/10^6Btu	West Outlet lb/10^6 Btu	Stack lb/10^6Btu
1	.71	.74	1.03	.70	.76	.79
2	.74	.79[3]	.95	.79	.82	1.01
3	.66	.71[3]	.99	.78[3]	.78	.96

Phase III, March 1980

Run No.	East Inlet lb/10^6Btu	West Inlet lb/10^6Btu	Theoretical lb/10^6Btu	East Outlet lb/10^6Btu	West Outlet lb/10^6Btu	Stack lb/10^6Btu
1	.76	.69	.82	.70	.68	.81
2	[4]	.67	.81	.69	[4]	.75
3	[4]	.67	.81	.65	[4]	.78

Phase IV, August 1980

Run No.	East Inlet lb/10^6Btu	West Inlet lb/10^6Btu	Theoretical lb/10^6Btu	Stack lb/10^6Btu
1	.84	.76	.96	.84
2	.89	.79	.94	.95
3	.88	.78	.96	.83

NOTES

[1] These concentrations are suspected of being low because of the high negative pressure pulling the absorbing solutions forward, thereby resulting in the absorbed SO_2 not being analyzed.

[2] Assumes all sulfur is converted to SO_2.

[3] Based upon only one of two samples for this run.

[4] No data.

Table VI. GCA Test Results

Test I, February 1979

Results Of Particulate Testing EPA Method 5

Run No.	East Inlet gr/scf	West Inlet gr/scf	East Outlet gr/scf	West Outlet gr/scf	Stack gr/scf	Stack lb/10^6Btu
1	1.03	1.57	0.011	0.019	1/	1/
2	0.99	1 68	0.007	0.005	0.009	0.018
3	1.34	1.20	0.004	0.008	0.008	0.016
4	2.21	1.36	0.004	0.007	0.012	0.024
5	1.53	1.02	0.001	0.002	0.004	0.007
6	1.36	2.36	0.005	0.042	0.017	0.034

Results of SO_2 Testing EPA Method 6

Run No.	East Inlet lb/10^6Btu	West Inlet lb/10^6Btu	East Outlet lb/10^6Btu	West Outlet lb/10^6Btu	Stack lb/10^6Btu
2	1/	0.91	0.82	0.95	1.10
4	0.98	0.80	0.94	1/	1/
6	1.10	0.61	0.68	0.64	0.74

Results of NO_x Testing EPA Method 7

Run No.	East Inlet lb/10^6Btu	West Inlet lb/10^6Btu	East Outlet lb/10^6Btu	West Outlet lb/10^6Btu	Stack lb/10^6Btu
2	1/	1/	0.60	0.69	1/
4	0.55	0.50	0.52	0.53	0.51
6	0.63	0.53	0.48	0.55	0.47

Results of SO_3 Testing EPA Method 8

Run No.	East Inlet ppm	West Inlet ppm	East Outlet ppm	West Outlet ppm	Stack ppm
2	0.27	0.79	0.95	0.72	1.10
4	2.07	0.67	0.60	0.82	1/
6	2.56	1.96	1.81	1.67	1.86

Test II, June 1980
SPS/GCA Joint Test

Results of Particulate Testing

Run No.	East Inlet gr/scf	West Inlet gr/scf	Theo-retical 3/ gr/scf	Stack gr/scf	Stack lb/10^6Btu
1	2/	2.30	2.13	.015	.032
2	1.92	1.86	2.22	.019	.037
3	1.38	1.31	1.95	.008	.016

NOTES

1/ No data this run.
2/ Invalid test.
3/ Based upon stoichiometric flue gas flow, coal flow, coal analysis and 70% fly ash generation (dry basis).

After the first several months of operation it became apparent that the original choice of fabric was not going to give the expected pressure drop. Several more months of operation also made it clear that the fabric was experiencing a high rate of failure.

Failure of the original fabric made it necessary for SPS to engage in a fabric filter evaluation program in order to find a fabric that would give satisfactory performance. A review of SPS's experience with fabric testing and analysis of those tests is presented in a recent paper titled "SPS Experience With Fabric Filtration" (4).

In May, 1979, a decision was made to rebag the entire fabric filter system before the summer peak load. Not only was the pressure drop excessive, but the original bags had a high failure rate, and SPS could not risk curtailing generating capacity because of the fabric filter system.

The Unit 2 baghouse was rebagged in June, 1979. Most of the compartments were equipped with fiberglass bags finished with 10 percent Teflon (Criswell Style 442-57DC2) or another fiberglass bag coated with a proprietary finish (Criswell Style 449-I580). Selection of these cloths was based on an evaluation of test compartments 21 and 23 which were rebagged in January, 1979. SPS will continue to document its experience with fabric wear and share its findings with other utilities interested in filtration technology.

CONCLUSION

Despite first-time difficulties with operating and maintenance parameters, SPS is pleased with the overall performance of the Harrington Unit 2 baghouse. The EPA study allowed SPS to focus on problems unique to a baghouse as large and with as many variables as the one at Harrington.

Results of the special testing program are significant in that they show Unit 2 can operate consistently with the old New Source Performance Standard (0.1 lb./10^6 BTU). However, the applicability of using SPS's experience to set industry-wide standards may be questioned because of SPS's unique fabric experience, cleaning problems, and less than ideal sampling locations. Improvements in particulate removal will need to be made before Harrington's Unit 2 can consistently meet .03 lb/10^6 BTU, although the data SPS collected during its special testing program is consistent with Unit 2 operating conditions.

SPS will continue to monitor the performance of the baghouse for the next four years. In addition, an economic analysis will be performed and fabric studies will be conducted in an EPA-sponsored pilot baghouse on stream with Harrington Unit 2.

ENDNOTES

1. Ladd, K.L., Faulkner, G.R., and Kunka, S.L., "Fabric Filter System Study: First Annual Report," EPA-600/7-79-183, August 1979.
2. Ladd, K.L., Chambers, R.L., Plunk, O.C., and Kunka, S.L., "Fabric Filter System Study: Second Annual Report," Contract No. 68-02-2659, August 1980.
3. Faulkner, G.R., Ladd, K.L., "Start-up, Operation and Performance Testing of Fabric Filter System," 3rd International Fabric Filter Forum, Phoenix, Arizona, September 1978.
4. Chambers, R.L., Ladd, K.L., and Kunka, S.L., "SPS Experience With Fabric Filtration," 5th International Fabric Filter Forum, Phoenix, Arizona, January 1981.

A SUMMARY OF PERFORMANCE TESTING OF THE APITRON ELECTROSTATICALLY AUGMENTED FABRIC FILTER

by
Dennis Helfritch
and
Lotar Kirsten

AIR QUALITY DIVISION
AMERICAN PRECISION INDUSTRIES, INC.
Charlotte, N.C.

ABSTRACT

The Apitron filter is currently the only commercially operating electrostatically augmented fabric filter. As such it has been intensively investigated by industry and governmental agencies over the past several years. A large amount of performance data has been gathered. Following a brief description of Apitron operating principles, this data is reviewed and compared for consistency. General conclusions are drawn from the data regarding performance improvements which result from electrostatic augmentation.

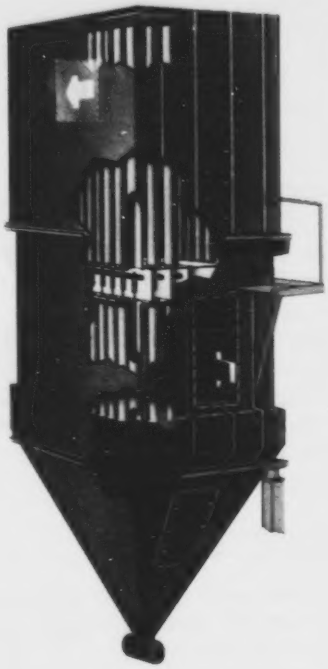
INTRODUCTION

In recent years a considerable amount of interest has been directed toward augmenting the filtration process by means of electrostatics. Many researchers have been actively engaged in theoretical and experimental aspects of electrostatic filtration, and funding for this type of research has increased dramatically. A recent symposium sponsored by the Fiber Society and the Filtration Society was devoted entirely to this subject.[1] The reasons for the interest in electrostatic filtration center about the potential of these techniques to reduce energy usage and increase submicron collection efficiency.

There are several techniques by which electrostatics can be applied to filtration. Particles or fibers or both may be charged, and electrostatic fields may be applied in different ways. These techniques and several combinations have all been attempted, and the interesting result is that they all improve filtration performance.

Almost all of the work, both theoretical and experimental, that has been done in this field so far has been in the area of basic studies. Modeling work, involving single and multiple fibers and particle trajectories under the influence of various electrostatic forces has been done. Experimental work, primarily with bench scale equipment and patch filters, has been done. While this work is essential and provides a base for future work, the results so far achieved cannot be used to predict the performance of commercial units, which are operated continuously for periods of years, during which the fabric is frequently pulsed, shaken or flexed. Because of this, the field testing of commercial and pilot scale Apitron units can yield valuable information.

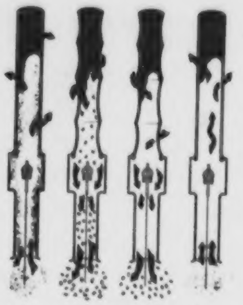
Figure 1



The Apitron electrostatically augmented fabric charges particles prior to their filtration by conventional bags. As shown in Figure 1, incoming airflow enters the charging section in the area below the walkway. The flow then passes upward through the tubes, where the particulate is charged and where some is deposited. Flow continues upward past the tubes, into and through the bags, where the final filtration of the charged particulate takes place. Clean air exits the unit at the exhaust, located at the top of the baghousing section.

Periodically, the deposit of particulate is cleaned from the tube and fabric. Six bags and tubes are cleaned of deposited dust at one time. This cleaning is initiated when an electrical pulse from the control box opens one of the twelve diaphragm valves for 1/10 second. Compressed air jets downward from six nozzles, each directly above a tube and concentric to a discharge electrode. The jet of air flowing downward through the tube entrains and mixes with a secondary air flow, and the collector tube is swept clean of deposited dust by the mixture of high velocity air. The secondary airflow, passing from the outside to the inside of the bag, snaps the bag inward and dislodges dust deposit from it, see figure 2.

Figure 2



THREE TEST PROGRAMS

Most test programs involving novel devices seek to document the efficiency and energy consumption of the device and then compare these results with those previously obtained for conventional devices. These comparisons are usually hindered by the fact that the conditions under which the two devices had been tested are invariably somewhat different. Completely valid comparisons can only be made when the two devices are simultaneously tested under identical conditions. The testing of electrostatically augmented filtration devices, however, offers the opportunity to switch off the electrostatics and hence tests the device as a conventional filter. This type of test minimizes the problem of comparisons.
We will therefore be primarily concerned with Apitron testing in which data was taken with and without electrostatic augmentation, and we will not make a strong attempt to compare Apitron performance with that of conventional fabric filters.

The Apitron has been tested by several industrial and governmental agencies, as well as its manufacturer and users. All testing has included data concerning collection efficiency and pressure drop, and data has only been recorded after several hundred hours of continuous operation. We will review three of these test programs individually.

AMERICAN FOUNDRYMEN'S SOCIETY

The object of this study [2] was to identify control devices which would be suitable for use in foundry process air recirculation. The foundry cleaning room was used as a potential recirculation application, and five conventional baghouses were efficiency tested as controls. Subsequently, several pilot scale model devices, including the Apitron, were then efficiency tested on the cleaning room exhaust of the General Motors Central Foundry. The inlet particulate was 900mg/m^3 of mostly iron oxide and silica, with a mass mean diameter of 3 microns. Only total particulate efficiency testing was done, and only for the electrostatically augmented case. The air cloth ratio was 5 CFM/sq. ft. and bag cleaning was off line, once every two hours. The results are show in Table 1.

Table 1 AMERICAN FOUNDRYMEN'S SOCIETY
Recirculation Test Results

	Inlet (MG/M^3)	Outlet (MG/M^3)	Efficiency
Best AFS Baghouse	1049	7.2	99.31
Worst AFS Baghouse	1714	66.1	96.14
Average AFS Baghouse (5 tested)	1755	39.7	97.75
Required for Recirculation	1755	1.5	99.91
Apitron (OHS #1)	1054	.19	99.982
Apitron (OHS #2)	743	.11	99.985

EPA

In 1978 a full scale Apitron module was tested under the EPA novel devices evaluation program [3]. 13 x 10^3 mg/m^3 of redispersed silica dust with a mass mean diameter of 25 microns was filtered at a 6 CFM/sq. ft. air cloth ratio. Bag cleaning was on line, each bag cleaned every eight minutes. Fractional efficiencies and pressure drops were measured for operation with and without electrostatic augmentation. A chronological view of the testing is shown in Figure 3. In this Figure the application of particle charging is given in terms of corona power (voltage x current), and obviously no particle charging occurs at zero corona power. The effect of particle charging on penetration and pressure drop can be easily seen.

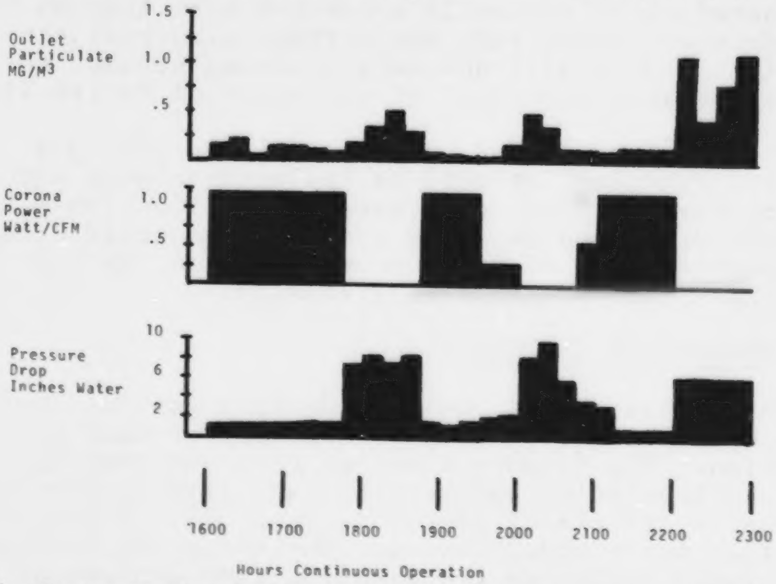
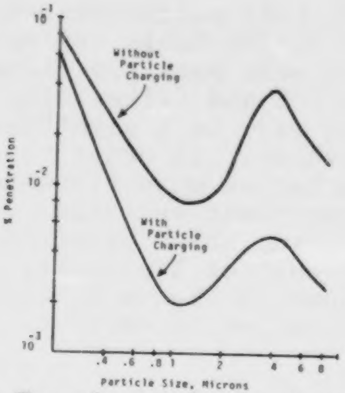


Figure 3

Figure 4 shows typical fractional efficiency curves for this application for filtration with and without electrostatic augmentation. It can be seen from these curves that, for this particular test, electrostatics exerts a stronger influence on larger particles than on smaller particles, there being an order of magnitude difference in penetration at 4 microns, but only a factor of two at 0.4 microns.

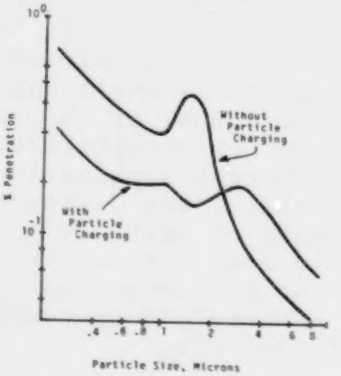
Figure 4



NIOSH

As with the American Foundrymen's Society, the object of this study was to identify control devices which would be suitable for plant air recirculation applications. Several pilot scale devices, including the Apitron, were efficiency tested on a weld shop ventilation system. The inlet particulate was 12 mg/m^3 of welding fume, with a mass mean diameter of .65 microns. Bag cleaning was off-line, once every eight hours, and air cloth ratio was 6.5 CFM/sq. ft. The results of fractional efficiency testing is shown in Figure 5. In this case, in contrast to the EPA tests, electrostatics has the largest influence on small diameter particles.

Figure 5



SUMMARY OF RESULTS

At this point we wish to formulate some general statements concerning electrostatically augmented fabric filtration, based upon the results of the work reviewed above. There are several similarities and several differences among the operational parameters of the three test programs. Gas temperature for all tests was ambient (about 70 F.). The filtration fabric for all tests was 11 ounce/sq. yd. polyester felt, and the corona power level for all tests was between .23 and .29 watts per CFM. Basic differences from test to test was of course the amount and the size distribution of the inlet particulate, and the type of bag cleaning (on vs. off line).

Table 2 summarizes the test parameters and results. The independent variables of the Table are essentially the inlet concentration and mass mean particle diameter, and the dependent variables are penetration and filter drag. Corona power and air cloth ratio do not vary in a significant way and can be considered fixed variables. In order to assess the influence of the independent variables on performance, graphs were constructed of each dependent variable versus each independent variable. The only paring which produced a physically meaningful result was that of % penetration versus mass mean diameter. This is shown in Figure 6, and the strong effect of particle size on penetration is obvious.

Figure 6

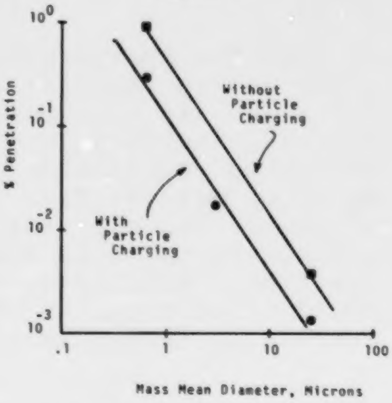


Table 2

SUMMARY OF RESULTS

Test	Corona Pwr. (watt/CFM)	Inlet (Mg/m^3)	Particle MMD (micron)	ACR (CFM/ft^2)	Penetration (%)	Drag ("H$_2$O/FPM)
AFS	.26	9×10^2	3	5	.017	.16
	0			5		.52
EPA	.29	12.7×10^3	25	5.8	1.3×10^{-3}	.48
	0			5.0	3.8×10^{-3}	1.72
NIOSH	.23	12.4	.65	6.5	.30	1.54
	0			6.5	.90	2.54

CONCLUSIONS

Table 3 summarizes the effect on performance caused by the utilization of electrostatics, where the penetration and filter drag results are given in terms of the ratio of their values obtained with and without electrostatics. Considering that three substantially different applications were used as a source of inlet particulate, the degree of performance enhancement brought about by particle precharging is remarkably consistent. From Table 3 we can say that electrostatic augmentation by means of particle charging prior to filtration yields approximately a threefold decrease in penetration and a twofold decrease in filter drag.

Table 3 EFFECT OF PARTICLE CHARGING

Test	% Penetration Elect/non-elect	Filter Drag Elect/non-elect
AFS	----	.31
EPA	.34	.28
NIOSH	.33	.61
AVE.	.34	.40

It should be remembered that these conclusions are derived from a varied, but extremely small data base. They are meant only to be qualitative guidelines as to what can be expected from electrostatic augmentation. In addition, these conclusions can only apply to the case of charged particles, and the application of electrostatic fields to filtration cannot be expected to produce similar results.

On the other hand, the results given are currently the only available results for long term operation of a commercial scale electrostatically augmented fabric filter. As such, the results can provide valuable insights to this emerging technology.

ENDNOTES

1) E.R. Frederick, "Fibers, Electrostatics, and Filtration: A Review of New Technology, "JAPCA, Vol. 30, No. 4,pp.426-431.

2) R. W. Potokar, "Foundry Process Air Recirculation, " JAPCA, Vol. 29, No. 1, pp 18-21.

3) L. G. Felix and J. D. McCain, "Apitron Electrostatically Augmented Fabric Filter Evaluation, "EPA-600/7-79-070.

4) M. L. Holcomb and R. C. Scholz, "Recirculation of Industrial Exhaust Air Pilot Study, "To be published by NIOSH.

FABRIC FILTER OPERATING EXPERIENCE FROM SEVERAL MAJOR UTILITY UNITS

By: Owen F. Fortune

Richard L. Miller

Eric A. Samuel
Buell Emission Control Division
Envirotech Corporation
Lebanon, Pennsylvania 17042

ABSTRACT

This paper presents the field operating experience from several major utility units. Reverse air fabric filter units operating experience from pulverized coal and cyclone-type boilers are presented. Startup experience with different firing techniques (coal, oil assist, gas) are presented. Field pressure drop data are correlated with a model. This field correlation demonstrates the dependence of pressure drop with the flyash particle size distribution, grain loading density, cleaning, and air-to-cloth ratio. This model explains the high pressure drop experienced by some units on lignite coal. Flyash particle size distributions from various compartments and within compartment are compared for a few units to investigate the industry's conjecture of variable particle size to different compartments.

INTRODUCTION

The successful use of baghouses in minimizing particulate emissions from coal-burning power plants is now in its seventh year. Yet, there is still debate over what factors are important in successfully designing and operating a utility baghouse. The purpose of this paper is to recount the operational factors that Buell has found to be important, and some of the conclusions that we have drawn from our experience and mathematical modeling work.

BAGHOUSE DUST AND GAS DISTRIBUTION

Much has been written (1, 2) about the problems of obtaining an even distribution amongst both the compartments and the bags of a large baghouse. This debate has gone on in spite of the fact that, unlike an electrostatic precipitator, the pressure drop across the cleaning elements is much greater (2 to 4" W.G.) than the velocity head of the dusty gas (typically 1/2" W.G. in the inlet manifold). Thus, if initially one area of the compartment has a thinner filter cake on the bags than in the rest of the compartment, the flow to that area will increase, and soon cause the filter cake in this area to increase more rapidly than in the rest of the compartment. Soon, cake thickness and bag gas flows will equalize throughout the compartment.

Our experience has been that obtaining equitable dust/gas distribution is a relatively easy thing to do, provided that four simple rules are followed:

A. Tap off from only the bottom - or at least near the bottom, of the inlet manifold,
B. Taper the inlet manifold so that roughly the same gas velocity is maintained along its length,
C. Be sure that the hydraulic diameter of the compartment inlet valves is small relative to the local hydraulic diameter of the inlet manifold, and
D. Decelerate the gas and dust entering the baghouse, and accelerate the gas leaving it, in easy, gradual stages.

(A) is important because horizontal duct runs to the baghouse(s) are often long enough (several hundred feet) to permit the larger (greater than 30 microns) dust particles to settle towards the lower part of the duct. Tapering the floor - rather than the roof - of the inlet manifold and taping off the manifold's upper portion, practically insures that the larger, heavier dust particles will be swept to the most downstream baghouse's compartments.

(B) and (C) simply mean design the inlet manifold to function as a plenum whose volume is large compared to its orifices. If this principle is neglected, then the need for custom-tailored compartment inlet turning devices rears its ugly head.

(D) takes into account the fact that the gas passing through a baghouse goes through at least six 90° turns. Obviously, it is necessary to smoothly decelerate and accelerate and turn the gas in order to prevent the formation below the compartment tubesheets of combinations of large, low-speed eddies and small, high-speed jets. This is done by first halving the gas momentum as it passes through the relatively small inlet valves, and then providing horizontal and vertical vanes inside the hopper to finish turning and decelerating the dusty gas. For example, an inlet manifold velocity of 3600 fpm would be reduced to 2500 fpm going through the inlet valves and then to the order of 500 fpm while passing under the bags. Fine-tuning the details of the hopper gas flow is the most important reason behind doing a baghouse geometric model study (3).

The importance of Items (C) and (D) is illustrated in Table 1, In an early Buell utility baghouse handling 380,000 ACFM, inlet valves were sized for a velocity of about 1000 fpm, while later designs have valve entrance design velocities between 2000 and 2500 fpm. In the former case, a coarser dust was found in the filter cake of bags in the upstream compartment, indicating a mildly uneven dust distribution along the baghouse length. For the high-speed inlet valve design, there is no significant difference in filter-cake mean particle size between compartments.

TABLE 1 - BAG FILTERCAKE, MEAN PARTICLE SIZE (MICRONS)

	380,000 ACFM BAGHOUSE "LOW VELOCITY INLET VALVES"	600,000 ACFM BAGHOUSE "HIGH VELOCITY INLET VALVES"
UPSTREAM COMPARTMENTS:	10.3	6.0
MIDDLE COMPARTMENTS:	7.4	6.1
DOWNSTREAM COMPARTMENTS:	7.0	5.9

Two other dust distribution questions are whether coarser dust winds up going up to the bags on one side of a compartment, and finer dust to the bags at the other end, and whether the filtercake at the bottom of a bag has coarser dust than the filtercake at the top of the bag. Buell's experience - as illustrated in Figure 1 - is that with properly designed inlet valves and hopper flow control devices, there is NO noticeable particle size gradient in a baghouse compartment (4).

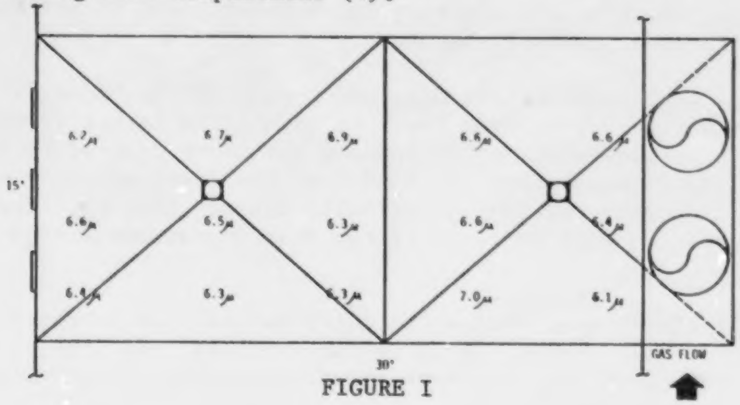


FIGURE I

Compartment Filtercake Mean Particle Size
Dust Distribution (Microns)

Using Stokes Law, the maximum terminal velocity for a falling particle in a gas flow can easily be computed:

$$\text{Maximum Drop Velocity (fpm)} = 7.2 \times 10^{-6} \frac{\text{(dust density)}}{\text{(gas density)}} \left[\begin{matrix}\text{mean particle} \\ \text{size (microns)}\end{matrix}\right]^{2} @300°\text{F}$$

For a 35' long, 12" diameter bag, the bulk velocity through the entrance thimble is of the order of 250 fpm. Thus, for 30 micron particles, only the top 6% of the bag would have a noticeably coarser dust. These theoretical considerations are in agreement with our field experience:

TABLE II - VERTICAL BAG FILTERCAKE MEAN PARTICLE SIZE

(11.5" Ø x 34'-8" L. BAG)

		SIZE (MICRONS)
TOP	-	5.2
MIDDLE	-	5.2
BOTTOM	-	5.0

BAG CLEANING DESIGN PHILOSOPHY

Once the dust and gas have been evenly brought to the thousands of bags in a baghouse, the next design consideration is how to set up the bag cleaning system. Two important factors to consider are:

A. Optimum Number of Compartments

Typically, this is in the range of 8 to 16 compartments per collector, with the average being 10 to 12. This results because:

1. Having too few compartments causes large pressure drop spikes as a result of taking too large a percentage of cloth off line during cleaning, while

2. using too many compartments can cause the time-averaged baghouse pressure drop to be high due to the fact that it will take hours to properly clean down all the compartments. This forces you into a continuous cleaning mode just to maintain reasonable pressure drops (i.e., if you initiate cleaning at 4.5" W.G., by the time you cleaned all the compartments, it would be time to start all over again). Continuous cleaning does not allow any margin of safety in case of upset conditions, such as a wet coal pile, high ash coal, boiler tube leaks, etc.

B. Optimum Number of Bags per Compartment

As shown in Figure 2, the current trend in reverse air cleaned baghouses is towards more and more bags per compartment. Since it is relatively easy to get good dust and gas distribution in large compartments, the limiting factors on compartment size become (1) how long it will take to install a new set of bags, and (2) at what point does the width and depth of the compartment result in a hopper whose height and weight is excessive.

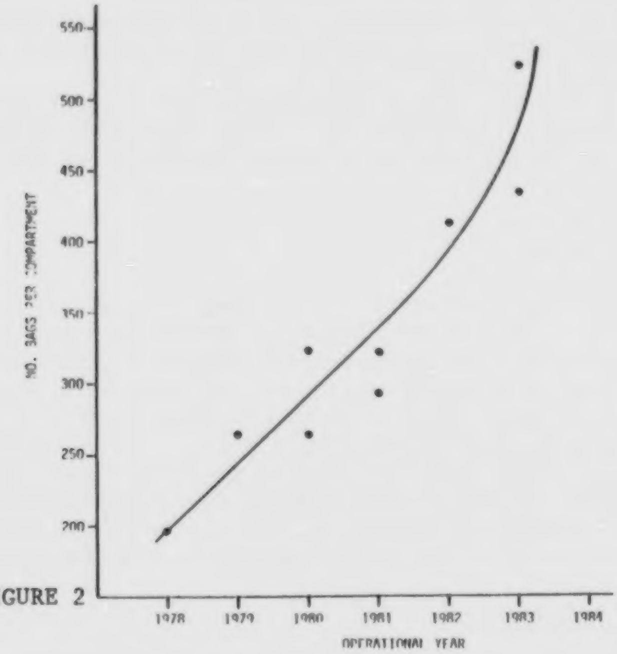


FIGURE 2

A three-man crew working in a reasonably cool (80 to 100°F) compartment can be expected to handle (remove old bags, install new bags, carefully check bag tensioning) about 50 bags in an eight-hour shift. Thus, a well ventilated compartment with three sets (tubesheet and bag top) of walkways could contain up to 450 bags and still be rebagged by nine men in three shifts. Similarly, it is logical to have as many as 600 bags in a compartment with four sets of doors.

REVERSE AIR CLEANING SYSTEM

How Not to Clean Bags

a. Using excessively high velocity reverse air flows, which can damage the bags by overflexing them.

b. Using cold reverse air (gas) can cause sub-dewpoint conditions in the compartment, resulting in an acid rain on the bags. This will result in high pressure drops and reduced bag life.

c. Too frequent cleaning of the filter cake exposes the fabric interstices. This causes "puffing" and opacity excursions due to particle migration through the fabric.

Proper Design Practice

a. Reverse air capacity at between 1-1/2 to 2 ACFM/FT^2 of active cloth per compartment. Buell typically designs for a ratio of 1.75:1 with at least a 14" W.G. capacity fan to provide the margin of safety needed in the cleaning system to handle conditions of high moisture, high dust loadings, sticky cake, etc., which can occasionally occur.

b. Slowly repressurizing a compartment after cleaning ensures that the bags will not suddenly reinflate ("pop") when the compartment is brought back into service after cleaning.

c. Maintaining reverse air relief flow at low levels (20% of design) at all times to keep reverse air ducts hot. This avoids sub-dewpoint reverse air temperatures and, hence, the spraying of acid rain on the bags during cleaning.

Cleaning Cycle Philosophy

The two common strategies used in cleaning reverse air baghouses are "Batch" cleaning and "continuous" cleaning. Batch Cleaning is initiated when the baghouse flange-to-flange pressure loss reaches a given level. All the compartments are cleaned in rapid sequence, and then left on line until the baghouse pressure loss again builds up to the trigger point. Continuous cleaning has the compartments cleaned on a rigid time schedule, regardless of the baghouse pressure drop. The advantages to batch cleaning are that the time-averaged baghouse pressure loss (and ID fan power consumption) is minimized. Continuous cleaning, however, avoids the brief (a few minutes) pressure spike that occurs when the first dirty compartment of the batch is cleaned.

Maximum Baghouse Pressure Drops

A considerable number of baghouse mathematical simulation models (5, 6, 7, 8, 9) have been proposed recently to try to explain why one baghouse will operate with a 5" W.G. pressure loss while another struggles with an 11" W.G. loss. Buell's experience is that a relatively simple extension of the classic Carman-Kozeny model, coupled with an elementary knowledge of boiler type (cyclone, tangential fired, etc.) and the expected coal and ash properties are sufficient to yield a realistic forecast of what air-to-cloth ratios are needed to meet a given maximum draft loss specification. The model Buell uses was adapted by T. Bechtel and O. Fortune from the Carman-Kozeny model. The C-K model was rewritten in terms of the important physical phenomena:

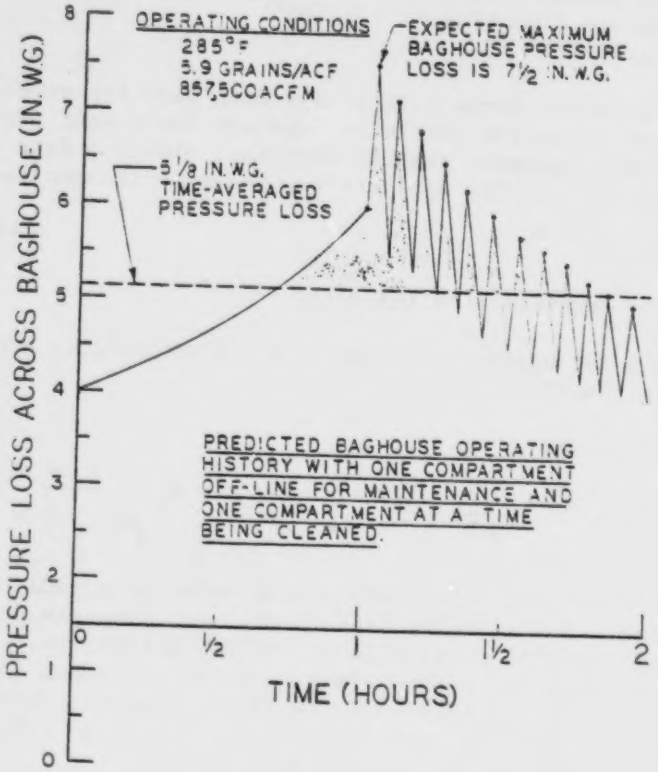


FIGURE 3

$$\Delta p = k_1 A + k_2 A^2 t D \qquad \text{(eq. 2)}$$

where
Δp = draft loss across filter cake ("W.G.)
A = air-to-cloth ratio (fpm)
t = time required for a complete cleaning cycle (hours)
D = flyash flow rate into the baghouse (gr/acf)

Since the field data used to establish k_1 and k_2 would be gathered from plants at different altitudes (and atmospheric pressures) and with different baghouse gas densities and temperatures, reference terms were added to the model to account for this:

$$\Delta p = k_1A + k_2A^2 \ t \ D \frac{H}{Hr} \quad \sqrt{\frac{Tr}{T}} = k_1A + k_3A^2 \ t \ \frac{DH}{\sqrt{T}} \qquad \text{(eq. 3)}$$

where H = atmospheric pressure at plant site ("Hg)
T = gas temperature (°Rankine = °F + 460°)
r = reference quantity

Since baghouse pressure drops have always been high for metallurgical applications involving submicron particles, and low for cement plant applications with coarse duct (greater than 30 microns), plotting data for a variety of industrial and utility applications leads to the conclusion that:

$$\Delta P \propto d^{-0.8} \qquad \text{(eq. 4)}$$

where: d = dust mean particle size (microns)

Buell's flyash pilot baghouse testing (8) later roughly confirmed this deduction by finding $\Delta P \propto d^{-0.7}$.

Thus, our model became

$$\Delta P = k_1 \ A + k_3 \ A^2 \ t \ \frac{DH}{\sqrt{T}} \left(\frac{dr}{d}\right)^{0.8} = k_1 \ A + k_4 \ \frac{A^2 \ t \ DH}{\sqrt{T} \ d^{0.8}} \qquad \text{(eq. 5)}$$

Buell has found that this relatively simple model is a good pressure drop prediction forecaster and also helps explain the high pressure drop problems at installations such as TUSI Monticello and SWEPCO Harrington. The results of a parameter study using the Bechtel-Fortune model are shown in Figure 4. The results agree with the conclusion of the flyash baghouse survey of Noll and Patel (7); that provided the air-to-cloth ratio is under 2:1, baghouse pressure loss is not a problem for utility applications.

BAGS, COATINGS AND WEAR

A. The vast majority of current utility boiler filter bags are made of fiberglass cloth. The only other present candidate fabrics are Nomex and acrylics. Both of these materials are seldom used because:

1. The maximum continuous temperature allowed with acrylics is 265°F. While some boilers do operate in this temperature range, it does not allow any room for excursions, and could lead to having to reduce load on hot summer days to protect the bags.

2. Nomex has a temperature limitation of 400°F and has poor resistance to acids. With some special finishes currently available, a maximum of 1-1/2% sulfur exposure is allowable but field data is minimal. Also, Nomex is approximately 50% more expensive than fiberglass.

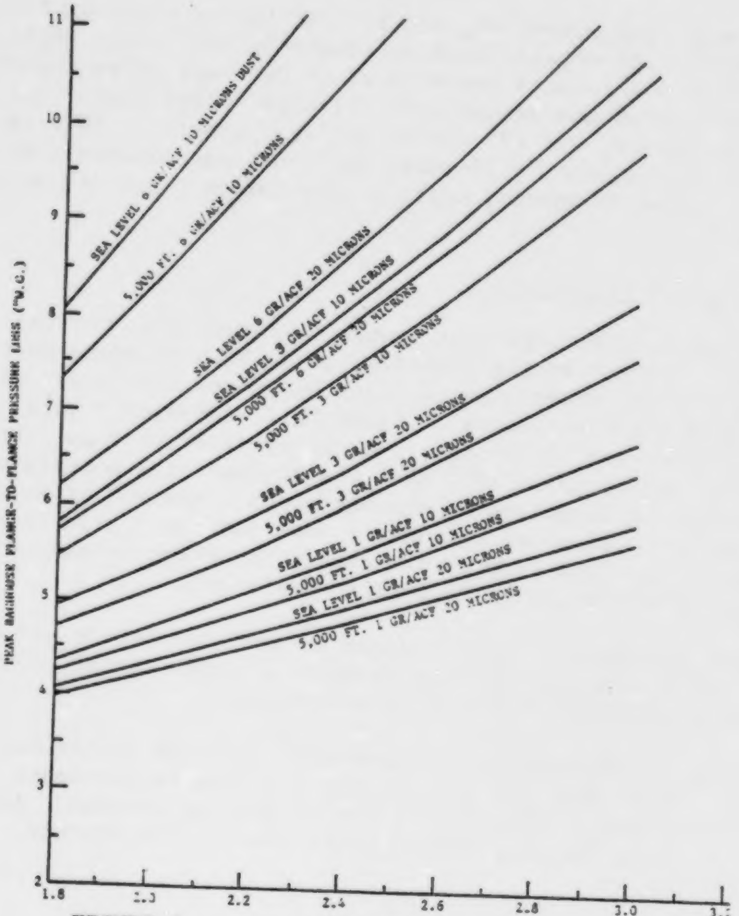


FIGURE 4

Thus, the final decision regarding the bag material will usually boil down to what weight of fiberglass cloth to use (9-1/2 oz./yd.^{2} versus 13-1/2 oz./yd^2)and what type of coating (Teflon B or acid resistant) to apply to the untreated fiberglass. Buell's standard practice is to prolong bag life by using 13-1/2 oz./yd^2 cloth where the design coals have high ash contents (i.e., over 15%), high sulfur contents (i.e., over 1-1/2%), or operating temperatures near the dewpoint. The more flexible 9-1/2 oz./yd^2 cloth is used for less vigorous, base loaded systems where we can take advantage of its greater flexibility and lower capital cost.

B. Fabric Protective Coatings

Fiberglass cloth ("Greige Goods") must receive proper chemical treatments (1) to protect the glass fibers from both acid and alkali attack, (2) to lubricate the fibers and thus improve abrasion resistance and flex endurance, and (3) to enhance its particulate release properties (allowing easier clean down and hence lower pressure drops). The two most commonly used coatings are Teflon B, and the so-called "acid-resistant" finishes (i.e., Q78, Acid Flex, Chemflex, etc.). The latter consist of silicon, graphite, teflon, and organic resins. While Teflon B does offer excellent lubrication and release properties, it does not offer the high degree of acid resistance needed with (1) high sulfur coals, (2) lower operating temperature, and (3) cyclic boiler operation. This is due to the fact that the various "acid-resistant" coatings encapsulate over two-thirds of the glass filaments, while a pure Teflon B coating encapsulates over one-third.

C. Bag Tensioning and Ring Spacing

1. Filter bags must be kept taut enough to ensure that the bags will not "pancake" together during cleaning; thus, both trapping dust and abrading the bag material, and slack enough so that their flexing during cleaning will remove at least half of the dust cake. This is achieved by sewing horizontal steel rings into the bags. Using cable theory, it can be calculated that the optimal ring spacing is a variable pattern (2 diameters at the bottom to a maximum of 4-1/2 diameters at the top) which provides a more uniform fabric flex angle along the bag. This reduces the chance of having localized flexure failure, particularly at the bottom of the bag.

2. Premature bag failure can be caused by both too little and too much tension (10). Recommended bag tension is approximately 50# for 8" diameter bags, and 75# for 12" diameter bags.

   Tensioning of the bags in a compartment has some similarity to tuning a piano. Start from the outside edges of the compartments and work toward the middle. Then wait a day or two and re-tune. After a few months on line, the bags should be re-checked for slackness due to creep-relaxation.

D. Quality Assurance and Quality Control for Bag Manufacture

To get high reliability out of bags calls for a firm QA/QC program. A good program (3) provides the baghouse supplier with the ability to trace all raw materials used during manufacture back to the original supplier, and due to various inspections and certifications, also ensures that these raw materials meet the specifications as required by the customer. Buell's experience is that good QA/QC procedures mean the difference between having on-site bag rejection rates of less than 1%, as opposed to as high as 20%, when a QA program was not carried out.

E. Bag Maintenance and Inspection

Periodic inspection and maintenance of bags is essential to prolong bag life. To provide a safe and workable environment, the following are desirable:

1. Compartment ventilation system is needed to cool internal compartment temperatures to approximately 20°F above ambient. Often the most

economical system is a combination of partial internal insulation and partial ventilation. Without this type of workable environment, the most one can expect of a man working in a HOT compartment is about 15 minutes inside, 20 minutes outside. Poor maintenance conditions will in the long run cause a reduction in bag care (i.e., bags near the hot wall not properly tensioned).

2. Doorway ventilation velocities under 1000 fpm, with maximum door opening being no wider than the lower walkways to avoid exposing the bags.

3. Opacity monitoring is a good method of checking for damaged bags. By cross-checking any opacity spikes with the cleaning cycle, one can identify the compartment with damaged bags.

PREPARATION FOR OUTAGES

For short outages (under two days), the baghouse can be bottled up if it has (1) good insulation (3" of mineral wool at least), and (2) the hopper heaters are left on. For long outages, the bags should be cleaned down at least 1/2 dozen times before the unit is brought off-line.

BAGHOUSE OPERATION DURING BOILER START-UP AND UPSET CONDITIONS

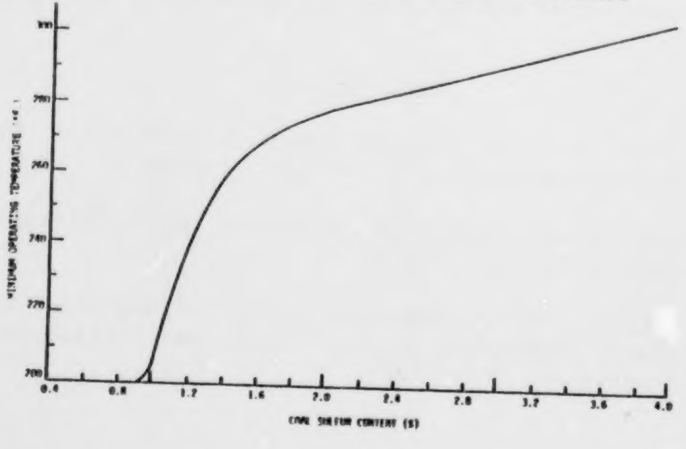
1. Start-Ups - Using Oil and Natural Gas

It is necessary to prevent the aromatic compounds formed during incomplete combustion of oil from entering the filter cake. So the baghouse is bypassed when burning either 100% oil or gas, until (a) baghouse internals are over 200°F, and (b) several coal mills are in operation.

Using a total liquids trap in the natural gas supply line to remove impurities helps minimize the problem in plants using gas fire-up.

2. Bypass Switchover Temperature

This is essentially a function of coal sulfur content.



The minimum operating temperatures shown are typically lower than pure gas-liquid SO_3 dewpoint curves due to the fact that they take into consideration the flyash alkali content.

3. Boiler Tube Leaks

Should a boiler tube leak occur, the baghouse chould be bypassed immediately to avoid possible damage to the bags. With superheater tube leaks, as long as the baghouse temperature remains above the new dewpoint temperature, this small increase in moisture will not affect the performance of the unit.

If a large tube rupture should occur in the economizer section of the boiler, a large amount of water will enter the baghouse, leaving a wet, muddy cake on the bags. Immediately, the baghouse should be put through 5-6 cleaning cycles to clean off as much of the cake as possible. Then, it should be bypassed and bottled up. After the damage to the boiler has been repaired, bring the baghouse on line on bypass until the bags can be dried out.

4. Air Heater Stoppages

This is not a problem for a baghouse, since you have about 5 minutes to bypass the baghouse before the temperature spike hits the bags, and the baghouse steel takes hours to heat up to over 500°F.

To avoid boiler upsets, the design bypass Δp should be equal to average baghouse Δp. This means velocities in the range of 5,000 to 7,000 fpm through the bypass valves.

CONCLUSIONS

We have attempted to show in this paper that by paying attention to a relatively small number of design parameters (dust loading, mean particle size, gas density, coal sulfur content) it is easy to rationally size a baghouse to operate with minimal, maximum and average draft losses. Then, given proper attention to bag manufacture and tensioning, the baghouse will perform successfully.

REFERENCES

1. P. R. Belkus. Dust and Flow Distribution on a 10 MW Unit. Fifth International Fabric Alternatives Forum, Phoenix, Arizona.

2. P. Bowen. Fabric Filter Model Studies Update. Fifth International Fabric Alternatives Forum, Phoenix, Arizona.

3. J. A. Hudson, et. al. Design and Construction of Baghouses for Shawnee Steam Plant. Second Symposium on the Transfer and Utilization of Particulate Control Technology, July, 1979.

4. W. Van Kleunen. Particulate Distribution Within TVA Shawnee Baghouses, ECD Ref.: 27475/S.O. 8898, January, 1981

5. R. Dennis, H. A. Klemm. A model for Coal Flyash Filtration. Journal Air Pollution Control Association 29:230 (1979).

6. J. R. Koscianowski, et. al. Filtration Parameters for Dust Cleaning Fabrics. EPA-600/7-79-031. January, 1979.

7. K. E. Noll, M. Patel. Evaluation of Performance Data From Fabric Filter Collectors on Coal Fired Boilers. Filtration and Separation. May, 1979.

8. E. A. Samuel. Research and Development of Test Baghouse at Martin Drake No. 6, City of Colorado Springs Mathematical Modeling Studies, December, 1979.

9. F. A. Horney. Coal Ash Characteristics: Do They Allow Predictability of Fabric Filter Performance. Fourth International Fabric Alternatives Forum, Phoenix, Arizona.

10. P. R. Campbell. Make fiberglass Bags Last Longer by Maintaining Proper Tension. Power. March, 1980.

11. E. W. Stenby, F. A. Horney, R. W. Scheck, D. M. Shattuck. Minimizing Boiler/Baghouse Impact. Power. December, 1979.

EVALUATION OF THE 25 MW KRAMER STATION BAGHOUSE:
TRACE ELEMENT EMISSION CONTROL

By

M. W. McElroy
R. C. Carr

Electric Power Research Institute
Palo Alto, California

The Electric Power Research Institute (EPRI) is currently supporting a major research program characterizing the emission control performance of fabric filter baghouses in coal-fired utility boiler applications. An integral part of this program is the determination of particulate matter chemical composition and collection. One such effort reported here is an evaluation of the Kramer Station baghouses of the Nebraska Public Power District.

Chemical analysis of particulate matter samples shows that the collection efficiency of over 35 individual major and trace elements was essentially equivalent to that of total mass. Size dependent chemical analysis results for nearly 30 elements over a 0.05-10 micrometer diameter size range further reveals that the vast majority of elements exhibit penetration profiles remarkably similar to total mass (Figure 1). A notable exception was selenium, which exhibited much higher penetration. Inlet size distributions indicated fine particle enrichment for several elements relative to the matrix elements. This enrichment behavior was still evident at the outlet of the baghouse (Figure 2), despite very low outlet emissions. Typical outlet size distributions are illustrated in Figure 3. A complete discussion and presentation of results are provided in EPRI Report CS-1669, "Kramer Station Fabric Filter Evaluation" (January 1981), prepared by Meteorology Research, Inc.

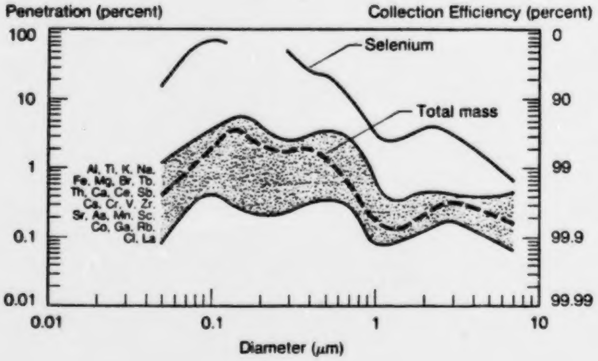


Figure 1. PARTICLE SIZE DEPENDENT ELEMENTAL PENETRATIONS.

Baghouse penetration profiles of most elements are contained in a relatively narrow band and closely resemble total mass. Thus, the total mass penetration may be a useful indicator of elemental penetrations. Overall baghouse collection efficiency was 99.7% at the time of these tests. Elements listed are all those for which complete inlet/outlet size distributions were obtained.

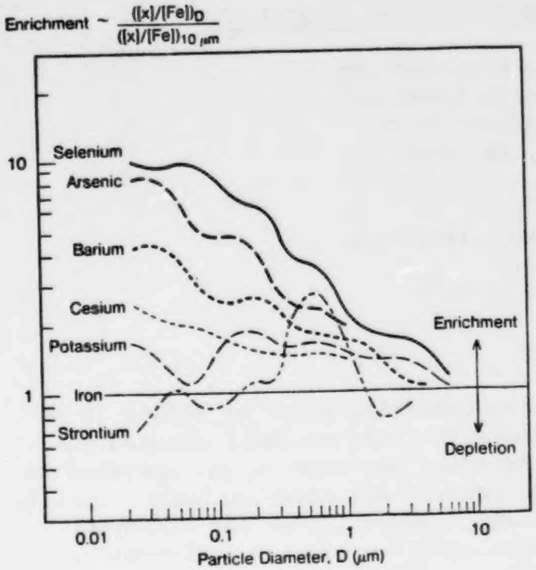


Figure 2. ENRICHMENT OF SELECTED ELEMENTS AT BAGHOUSE OUTLET

Enrichment is defined here as the concentration ratio of an element to iron at a specific particle diameter divided by the concentration ratio at a particle diameter of 10 micrometers. Iron was selected as the reference element because of the similarity of its size distribution to that of total mass.

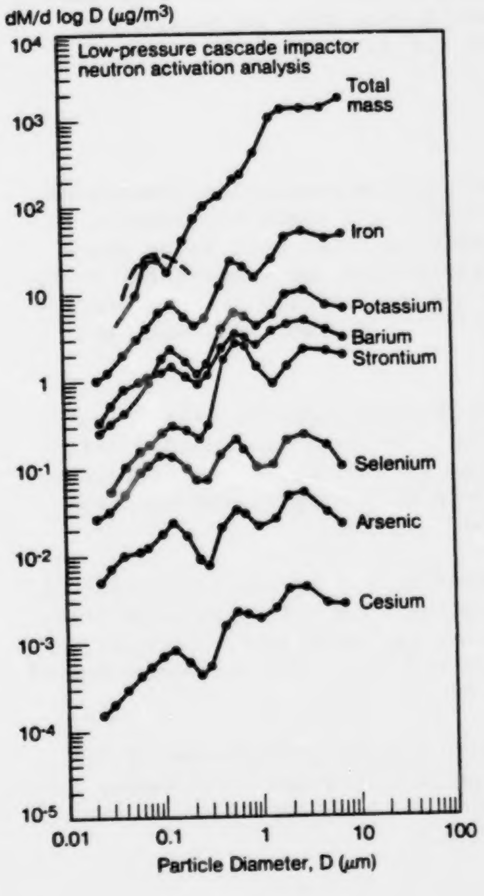


Figure 3. SIZE DISTRIBUTION OF SELECTED ELEMENTS AT BAGHOUSE OUTLET

Only 7 of the over 30 elements analyzed are shown for clarity. Elements are present over the entire particle size range and exhibit size distributions qualitatively similar to total mass. Results here and in the previous figures are based on neutron activation analysis of low pressure cascade impactor samples. Electrical aerosol size analysis (dashed line) independently confirms submicrometer size distributions.

CHARACTERIZATION OF A 10 MW FABRIC FILTER PILOT PLANT

By: W.B. Smith and K.M. Cushing
Southern Research Institute
2000 Ninth Avenue South
Birmingham, AL 35255

R.C. Carr
Electric Power Research Institute
P.O. Box 10402
Palo Alto, CA 94304

ABSTRACT

Data are reported describing the initial operating phase of EPRI's 10 MW Fabric Filter Pilot Plant. During these tests the main variable studied was the method of cleaning the bags. One of the four compartments was operated in a shake/deflate mode and the other three in reverse air cleaning mode. Significant differences were found in the operating pressure losses for different cleaning modes. The lowest pressure loss was experienced with Shaker/deflate cleaning while the highest was with reverse air and near continuous cleaning. Extended dwell times resulted in lower operating pressure for the compartments with reverse air cleaning. Detailed measurements were made to relate the operating pressure losses to the properties of the dust cake.

INTRODUCTION

Although the use of fabric filters in controlling particulate emissions from industrial processes is an established technology; their application to large electrical generating systems is relatively new. As more large units come on line and experience is gained, it is clear that the fundamental mechanisms that govern the operating pressure loss and reliability are not predictable or well understood. In most instances[1,2,3,4], however, the emissions are very low.

EPRI is conducting detailed tests of a 10 MW Fabric Filter Pilot Plant (FFPP) at the Arapahoe Emissions Control and Test Facility to build a data base relating the design, startup, and operating parameters to the efficiency, pressure loss, cost, and reliability. These data will support the electric utilities in designing more efficient full-scale systems.

The FFPP is a versatile system allowing flexibility in selecting most of the operating parameters (air/cloth ratio, cleaning mode, cleaning intensity, flow distribution, ash concentration, dwell time, bag materials, bag size, precoating, and preheating). During the test reported here, the variables tested were the bag cleaning method and dwell (or filtering) time.

The following sections contain a description of the performance of the FFPP during the first few months of operation and of detailed experiments that were performed to relate the measured performance to the properties of the aerosol/filter system. In the discussion section, the data are summarized and the dependence of the operating pressure loss on the properties of the dust cake is discussed.

OPERATION OF THE FABRIC FILTER PILOT PLANT

The FFPP contains four compartments, each equipped for independent operation. The system is designed for a nominal flowrate of 30,000 ft^3/min, but individual compartments can be operated at flowrates up to 15,000 ft^3/min. As shown in Figure 1, each compartment contains 36 bags in a 6x6 array. Shaker, reverse air, or combinations of these are available cleaning methods. The bag support assemblies and tube sheets are adjustable, allowing the evaluation of 22, 26, 30, and 34 foot bags of various diameters. Each compartment is equipped with a dirty gas inlet, compartment bypass, reverse air, clean air preheat, and clean air outlet duct. This arrangement allows complete flexibility in selecting the operating conditions for each compartment. Provision is made for the injection of flyash into the inlet to allow testing under a wide range of dust concentration. The entire system can be decoupled from the boiler for air load testing. The FFPP is controlled and all of the operating flowrates, pressures, and temperatures monitored by a dedicated micro-processor.

The FFPP is operated on a sidestream from a 110 MW, pulverized coal boiler burning "Energy" (0.3% S) fuel. In order to study the dependence of the FFPP operation upon the boiler condition, logs are kept of the primary operating parameters of the latter. Coal and ash samples are taken frequently for analysis, and NO_x and O_2 monitors are installed in the gas stream.

A variety of test methods are being used to measure the performance of the FFPP. For investigations of gas flow, s-type pitots, hot-wire anemometers, and smoke are used. For particulate measurements at the inlets, cascade impactors, cascade cyclones, mass trains, and a transmissometer are used. For particulate measurements at the outlets, cascade impactors, mass trains, special photometers, and a Fine Particle Sizing Stack Spectrometer (FSSS)* are used. An Electrical Aerosol Size Analyzer (EASA)** is used at the inlet and outlet to measure the size and concentration of submicron particles. Windows and lights are distributed throughout the system to allow visual observations during operation. Samples are cut from the bags for detailed analysis of the dust cake.

In preparation for startup the compartments were all equipped with woven[1] glass fiber bags coated with silicon/teflon/graphite (Albany International Q53-S3016 "Tri-Coat") 34 feet long and one foot in diameter. Compartment A was programmed for shaker/deflate cleaning. Compartments B, C, and D were programmed for reverse air cleaning. The bags in compartment A contain no rings. The others have eight support rings spaced about four feet apart. The ringed bags were tensioned to 75 lbs and the nonringed bags to 60 lbs. It was decided not to preheat or precoat any of the compartments because those procedures do not represent typical industry practice.

*Particle Measurements Systems, Boulder, Colorado
**Thermosystems Inc., Minneapolis, Minnesota

When shutting down, it was planned to purge the compartments with clean, heated air to avoid condensation of flue gas upon cooling, although two unplanned shutdowns occurred where purging was not possible with no apparent permanent detrimental effects. Arrangements were made to check all flows, pressures, temperatures, and particulate monitors around the clock.

After the initial startup period, all of the compartments with reverse air cleaning were put on time initiation instead of ΔP initiation because the increasing pressure loss led to continuous cleaning when operated in the ΔP initiation mode. Each compartment was set to a different dwell time in order to further investigate the effect of dwell time upon the pressure drop observed previously at the Kramer station.[3] Ultimately the system settled into a stable operating mode as shown in Figure 2. The operating parameters of the FFPP for these tests are summarized in Table 1.

Referring to Figure 2 the phenomenon first noticed at the Kramer station is confirmed. If a compartment is left on line longer without cleaning, the residual ΔP after cleaning and the slope in the ΔP vs. time curve are lower. This appears to be a clear indication that heavier dust cakes are easier to dislodge, which might be deduced intuitively. On the other hand, the dependence of the slope on the time between cleaning cycles is not as easily explained. Perhaps this is an indication that certain areas on fabric surface are more nearly cleaned to a "like new" condition.

TABLE 1. OPERATING PARAMETERS DURING THE FFPP TESTS

Compartment	Air/Cloth Ratio	Dwell Period	Cleaning Method
A	2.0 ft^3/acfm	$\approx$ 2 hrs	Shake/deflate, ΔP initiate, ± 2 inches, 2Hz
B	"	1 hr	Reverse air, timed, 1.5 ft^3/acfm
C	"	3 or 3.5 hrs	"
D	"	5 hrs	"

The curves shown in Figure 2 also offer a possible explanation for the reason that the tests where the reverse air cleaning was ΔP initiated (4.5 iwc) were unsuccessful. As the time between cleaning (dust load in bags) is reduced, the residual ΔP increases and the slope increases. Thus, any perturbation resulting in an increased ΔP will create an unstable situation driving the system toward a condition of continuous cleaning.

Two positive aspects of the bag cleaning experience can be derived from Figure 2. The first is that shaker/deflate cleaning appears to be a viable method, although not optimized during these tests. The second is that it can be seen to be advantageous to employ timed cleaning, rather than ΔP initiation, and extend the time--perhaps beyond five hours. From the second observation it was concluded that additional data and understanding of the cleaning phenomenon might be gained through artificially increasing the inlet mass concentration (dust accumulation rate) by injecting fly ash at the inlet.

The results of the ash injection tests are shown in Figures 3, 4, and 5 for compartments B, C, and D, respectively. No data are shown for compartment A because it was operated at a lower flow during these tests to reduce the load on the booster fan. Sufficient ash was injected to increase the mass concentration from 2.5 to 11.4 gr/scf. The pressure loss before cleaning and after cleaning and the rate of increase in pressure loss (slope of curves in Figure 2 are plotted vs. time. All three of these parameters were affected immediately by the injected ash. Filter cycles that were in progress when the injection began were characterized by increases in the slope of ΔP vs time and higher pressure drops. In subsequent cycles, however, the residual pressure drop (after cleaning) decreased for all three compartments. The ΔP before cleaning and slope were significantly lower in compartment B, but essentially unchanged in C and D. It should be noted that the total test period, 17 hours, was too short for any of the compartments to reach a stable condition. Compartment D, for example, only cleaned 3 times during the test. It is clear from these data that the additional dust load resulted in better cleaning within all three compartments. The improvement was greatest in compartment B where the dust loading on the bags was least under ordinary conditions. The improvement in compartment D was much smaller, perhaps indicating that the 5 hour cleaning period was near optimal for the normal (2.5 gr/scf) mass concentration and our cleaning sequence.

The data are shown plotted another way in Figure 6. Here the pressure loss before (ΔP_{BC}) and after (ΔP_{AC}) cleaning are shown plotted as functions of filtering time, with and without the ash injection. It appears from the curves that no advantage can be gained by extending the dwell time beyond about five hours. Although it is possible to reduce ΔP_{AC} by extending the filtering time, the problem of a high average ΔP remains. Thus further studies are planned to investigate means of cleaning the bags further.

Throughout the tests the efficiency of the compartments was very high--on the order of 99.99+% for the reverse air compartments and 99.95+% for the shaker compartment. Typical recordings of the outlet opacity (undiluted and normalized to a 10M stack) are shown in Figure 7. The emissions increase by about two orders of magnitude immediately after cleaning, but quickly subside to yield opacities less than 0.05% for the reverse air and 0.2% for the shaker compartments.

In an effort to interpret and understand the operating conditions of the FFPP observed during the startup and early operation periods, detailed analyses of fabric samples were undertaken. The thrust of these analyses was to characterize the residual dust layer as thoroughly as possible and to relate the observed properties to the operating ΔP and clean down effectiveness. The measurements included permeability tests, higher reverse air/cloth, photographs, thickness profiles, mass density, and size analysis. All of the measurements were made using swatches carefully cut from the top, middle, and bottom sections of the bags after the compartments were shut down.

Recall that during operation the bags in compartment A were shaken with reverse air assist at a ΔP of 4.5 iwc. Those in compartments B, C, and D were cleaned using reverse air (A/C of 1.5:1) at intervals of 1, 3, and 5 hours, respectively. Figure 9 contains photographs illustrating the remarkable differences in appearance from compartment to compartment and top to bottom. Notice the common formations of "nodular deposits" in compartments B, C, and D. Upon close examination, the nodules can be seen to be attached to fibers protruding from the main body of the bafric. Both the nodules and smooth cake are rather frangible and can be disturbed easily with a pencil. There is no evidence of any "cement" like properties. The swatches taken from the tops of the bags appear visually to contain a heavier dust cake then those from the bottom. It is surmised that an avalanche effect occurs during the cleaning cycle and that the lower parts of the bags tend to be swept clean. Vertical lines of smoother material can be seen in the swatches from compartments B, C, and D at positions when the bags folded during reverse-air cleaning.

The pressure loss vs. A/C of the filter material and residual dust layers was measured by clamping the samples into a standard 8 x 10 inch high-volume filter holder and measuring the pressure drop as flow was increased in the forward and reverse direction. Figure 8 shows ΔP vs air/cloth measured in the forward direction before and after running the swatches at reverse A/C of 4.1:1. It was surprising to find the more permeable cakes at the top in compartments C and D because the dust cakes appeared visually to be much heavier, and that although the bags had already been cleaned in the compartment at an A/C of 1.5:1, additional reductions in pressure loss were achieved by increasing the reverse air/cloth ratio to 4:1.

From these data it can be concluded that the flow through the bags during the filter cycle is strongly stratified immediately after cleaning from top to bottom of the bags. Greater flow occurs at the top in the reverse air compartments despite heavier dust loads and greater flow at the bottom in the shaker compartment. The pressure loss does not correlate well with mass of dust cake per unit area indicating that the packing density or size distribution may be different.

DISCUSSION

From the data described above it appears that the details of the gas flow and pressure loss are intimately related to properties of the dust cake. This dependence results in large variations in flow along the length of the bags after cleaning. It is not known how long this unequal flow persists into the dwell period.

Heavier dust cakes are easier to remove than light ones, indicating that extended dwell times might allow operation at lower average pressure than very short dwell times or continuous cleaning. Some increase in maximum ΔP may be required to accumulate the heavier cakes, however, and additional tests will be required to optimize the operating cycle.

Published literature on the removal of collected dust from bags and the factors determining the pressure loss are scarce. Dennis[5] has observed that "under field conditions, dust removal from woven glass fabrics cleaned by collapse and reverse flow may range from 5 to 35 percent, whereas mechanical shaking (2.5 cm amplitude at 8 Hz), may provide ~50 percent removal." Recently a paper written by Lembach and Penney[6] contained a discussion of "nodular deposits" formed in fabrics after many cleaning cycles. It is thought (although not confirmed) by the authors that these deposits, which cling to protruding fibers, are composed of fine particles and act as check valves offering little resistance to reverse flow but moving into voids to offer a high resistance to forward flow. These deposits have been observed by others (e.g. at Four Corners)[7] and by us. There is some speculation that the formation of hydrated salts in the cake make the particles more adhesive.

Ariman and Helfritch[8] have found that dust is removed more easily under conditions of high relative humidity. Sproull[9] reports that thick layers are removed (from ESP plates) more easily than thin ones and that the dust is more easily dislodged at high temperatures.

Although the physical forces governing particle cohesion and adhesion are such that individual small particles cling more tightly to one another and other surfaces than large particles. It is generally thought that layers of fine particles are less porous, but this rule of thumb is not supported by experimental data. Iinoya[10] has measured the porosity for polydisperse aggregates of particles of different size and composition. His data show that distributions of small mass median diameter have higher porosity (See Table 3.).

The relationship between the porosity measured in bulk powders and the operating fabric filter systems is yet to be established. The fabric structure may play an important role and the cake may collapse under the gas pressure to present a more impermeable barrier to flow.

Further studies will be required to relate the properties of the aerosol and dust cake to the operation of fabric filter systems. Future plans include: Tests with variable compartment flow to simulate large installation, long-term fly ash injection tests, a range of magnitude in the reverse air/cloth, extended dwell time for the shaker/deflate compartment, and a range of magnitude in the filtering air/cloth ratio.

TABLE 3. POROSITY* OF ACCUMULATED POWDERS (AFTER IINOYA AND YAMAMURA[10])

Powder	Surface Mean Diameter, μm	Porosity (ε) of Deposit
Talc	1.6	0.74 - 0.81
Flour	33	0.51 - 0.61
Flour	12	0.62 - 0.70
Clay	4.6	0.68 - 0.71
Wood Dust	6.0	0.90 - 0.91
Flue Dust	5.6	0.74 - 0.77
Flue Dust	0.24	0.94

*Porosity, ε, is defined in terms of the pressure drop by D'Arcy's

Equation:

$$\Delta P = \frac{C(1-\varepsilon)^2 S_v^2}{\varepsilon^3} \mu VT \text{ or } \Delta P - \frac{C\mu VT}{K}$$

where

ΔP = the pressure loss observed,
ε = the porosity,
S_v = the surface area of a unit volume of the cake,
μ = the viscosity of the gas,
V = the face velocity or A/C,
K = the permeability, and
T = the thickness of the cake.

ACKNOWLEDGEMENTS

Several individuals and organizations have contributed to the design and evaluation of the FFPP. The mechanical design, flow modeling, and construction was done by Lodge Cottrell Division of Dresser Industries. Lou Rettenmair, Richard Hooper, and Walter Puille of EPRI have made significant contributions during the construction, planning, and startup programs. Kaiser Engineers provide continuing support for the operation and modification of the unit. We have benefited significantly from the advice of Charles Gallaer, Engineering Consultant.

The data reported here were taken by Ray Wilson, Annette Duncan, and Myron McCallum of Southern Research Institute.

The continuing support of Public Service of Colorado is supporting the emissions control test facility and cooperating with us in this pilot program is greatly appreciated.

This work was supported by the Electric Power Research Institute under contract RP1129-8.

ENDNOTES

1. Ensor, D.S., R.G. Hooper, and R.W. Sheck. Determination of the Fractional Efficiency, Opacity Characteristics, Engineering and Economic Aspects of a Fabric Filter Operating on a Utility Boiler, EPRI Report No. FP-297, November 1976.

2. Huber, D.J. Start-up and Initial Operation of the City of Colorado Springs Unit #1, Baghouse Filter. (Presented at the 5th Fabric Filter Forum, Phoenix, Arizona, January, 1981).

3. Ensor, D.S., S. Cowen, A. Shendrikar, G. Markowski, G. Woffinden, R. Pearson, and R. Sheck. Kramer Station Fabric Filter Evaluation, EPRI Report No. CS-1669, January 1981.

4. Chambers, R. Operating Data - Harrington Station. (Presented at 5th Fabric Filter Forum, Phoenix, Arizona, January, 1981).

5. Dennis, R. and H.A. Klemm. Recent Concepts Describing Filter System Performance. (Presented at the Joint U.S.-Japan Seminar on Measurement and Control of Particulates Generated from Human Activities, Kyoto, Japan, November, 1980).

6. Lembach, R.F. and G.W. Penney. Nodular Deposits in Fabric Filters. J. APCA 29(8), August 1979.

7. Singh, U. Four Corners Units Four and Five Particulate Removal Project Filter-House Pilot Program. (Presented at 5th Fabric Filter Forum, Phoenix, Arizona, January 1981).

8. Ariman, T. and D.J. Helfritch. How Relative Humidity Cuts Pressure Drop in Fabric Filters. Filtration and Separation. March/April 1977.

9. Sproull, W.T. Fundamentals of Electrode Rapping in Industrial Electrical Precipitators. J. APCA 15(2), February 1965.

10. Iinoya, K. and M. Yamamara. Fundamental Experiments with Fabric Dust Collectors. Chem. Eng. (Japan) 20, 1956.

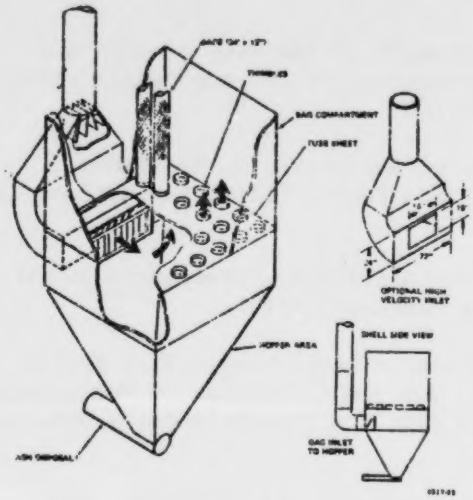

BAG COMPARTMENT
TUBE SHEET
OPTIONAL HIGH VELOCITY INLET
SHELL SIDE VIEW
HOPPER AREA
GAS INLET TO HOPPER
ASH DISPOSAL

Figure 1. Sketch of bag compartment with sections broken away to show arrangement of internal details.

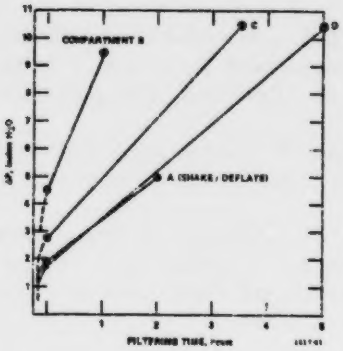


Figure 2. Typical ΔP versus time data for reverse air and shaker cleaning.

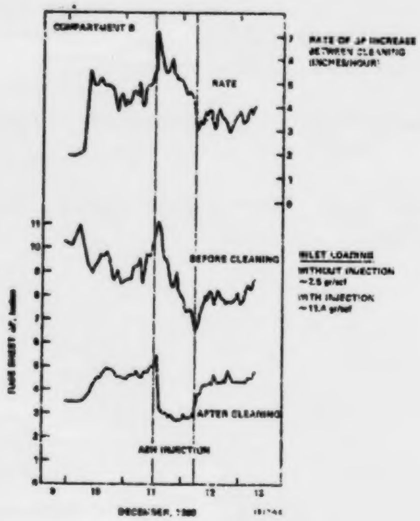


Figure 3. Tube sheet ΔP before and after cleaning and rate of ΔP increase for Compartment B during the period December 9-13, 1980. Ash injection was on for a period of seventeen (17) hours.

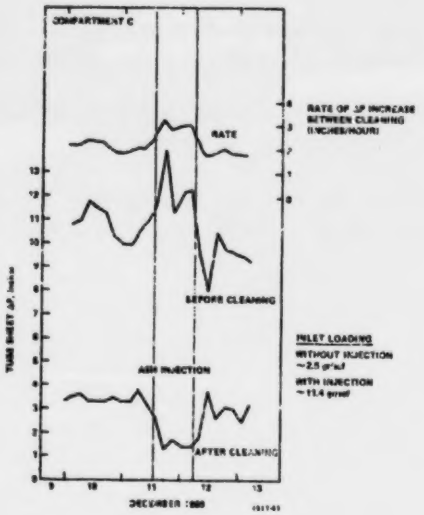


Figure 4. Tube sheet ΔP before and after cleaning and rate of ΔP increase for Compartment C during the period December 9-13, 1980. Ash injection was on for a period of seventeen (17) hours.

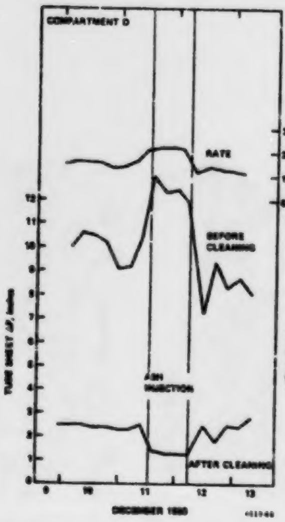


Figure 5. Tube sheet ΔP before and after cleaning and rate of ΔP increase for Compartment D during the period December 9-13, 1980. Ash injection was on for a period of seventeen (17) hours.

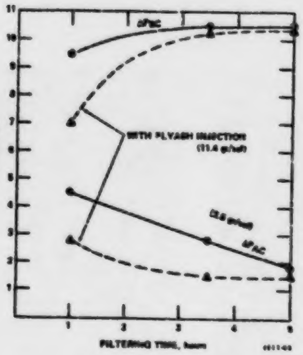


Figure 6. Pressure loss before (ΔP BC) and after (ΔP AC) cleaning the bags by reverse air for different filtering times.

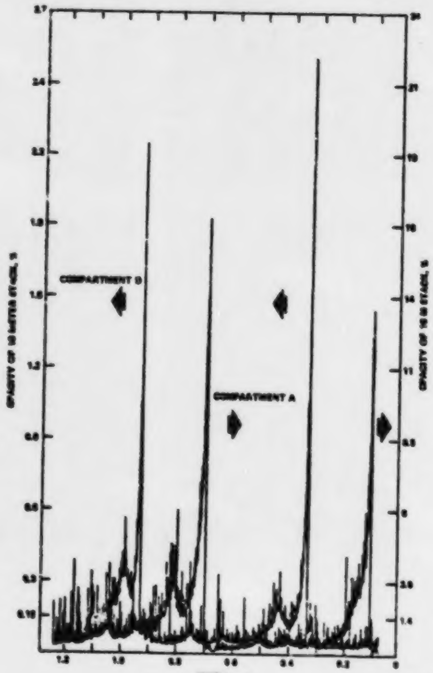


Figure 7. Typical response of the opacity monitors on Compartments A and B.

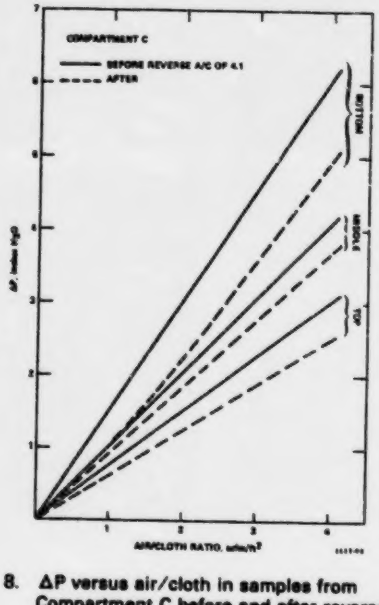


Figure 8. ΔP versus air/cloth in samples from Compartment C before and after reverse air tests at air/cloth of 4.1 acfm/ft^2.

Reproduced from
best available copy.

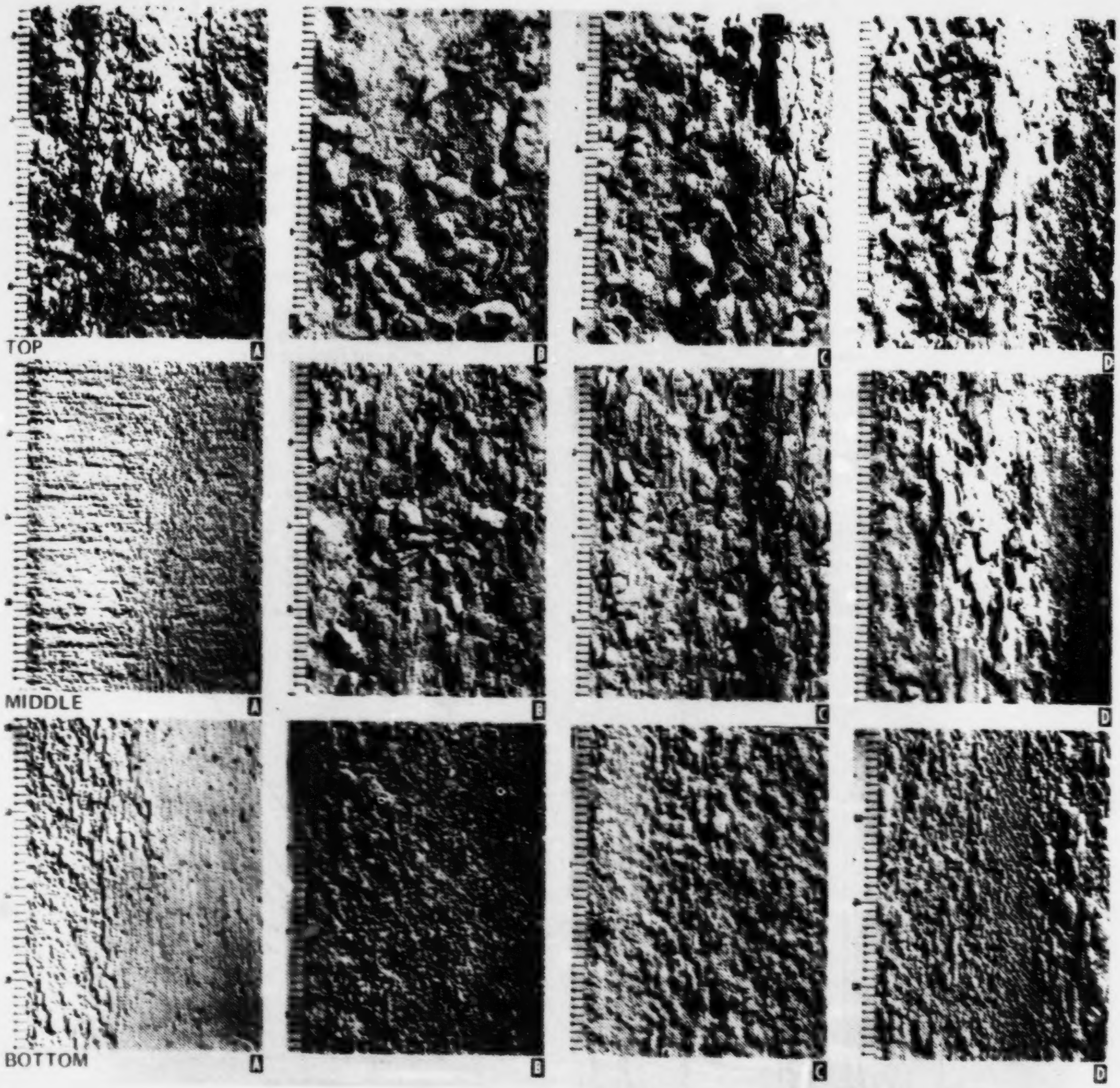

TOP
A
B
C
D
MIDDLE
A
B
C
D
BOTTOM
A
B
C
D

Figure 9. Photographs of swatches taken from bags in each compartment of the FFPP.

SPECIFYING A FABRIC FILTER SYSTEM

By: Ronald L. Ostop
Department of Public Utilities
Colorado Springs, Colorado 80947

David A. Single
Buell Emission Control Division
Lebanon, Pennsylvania 17041

ABSTRACT

In the last decade environmental regulations have required demanding technological advances on particulate control techniques. One particular challenge has been collecting fly ash from the combustion of low sulfur coal. Ten years ago, two of the choices available for collecting high "resistivity" coal ash were hot side precipitators and cold side precipitators with flue gas conditioning. Five years ago, fabric filtration began emerging as another alternative.

With the new application of this old technology, fabric filter baghouse applications have resulted in many successes, and in some instances, systems that were not so successful. So, the question arises, "How does one design and specify a fabric filter baghouse system that will be successful?"

Based upon actual design and operating experience, this paper presents the basic information needed to specify a fabric filter system that will provide cost effective operation. The discussion will include the conceptual requirements for specifying such parameters as air-to-cloth ratio, pressure drop, bypass capability, inlet and outlet valve requirements, pneumatic and electronic control systems, emergency control instrumentation, etc.

The operating principles of a baghouse are simple. By following fundamental steps in specifying a baghouse, the subsequent purchase and installation can be equally uncomplicated.

INTRODUCTION

Fabric filter baghouses are highly efficient and reliable particulate collection systems. These systems also demonstrate high availability with relatively low operating and maintenance costs. The key to such success is properly specifying a system which will meet the established need.

The first step is to define the parameters of the process system to be controlled. Such parameters include:

- Whether the boiler unit is continuous or cyclic.
- Whether the boiler is stoker-fired or burns pulverized fuel.
- What is the fuel used for ignition?
- What are the fuel characteristics?

- What is the maximum air flow rate?

- What are the maximum and minimum operating temperatures?

- Is there any flue gas desulfurization prior to the fabric filter system?

- What is the maximum ash and moisture content of the fuel?

- What operating pressure drop will be compatible with the complete process system?

The careful examination of the application and the emphasis of the physical phenomena of mass, momentum and heat transfer will avoid such problems at excessively high differential pressures and corrosion of the baghouse structure and auxiliary equipment. It will also help avoid erosion of the filter media and rotating equipment, while still resulting in no visible emissions being emitted from the stack.

Operating Principles

The application of fabric filtration is found in that branch of fluid mechanics describing the flow of fluids through a porous material. In theory, the collection mechanisms are described by processes of impaction, interception and diffusions. In practice, hot dust laden flue gases pass through a fabric filter leaving approximately 99.9% of the dust behind.

The fabric itself does not collect all of these particles. The fibers act as a substrate to capture and hold the larger particles which in turn act as the filter media for capturing the smaller particles. Therefore, the development of the filter cake during the initial conditioning period will determine the success of the operation of the baghouse.

Operational observations have shown that the filter efficiency increases with the increase of pressure drop across the filter during the development of the filter cake. Once the filter cake has been established, the increase of pressure differential will stabilize and the ultimate collection efficiency will be established.

Conceptual Design Considerations

Air-to-Cloth Ratio

The air-to-cloth ratio is the major parameter in determining the cost of the fabric filter system. It will determine the physical size of the baghouse and its auxiliary equipment, thus being a major factor in the cost of material and labor. The air-to-cloth ratio is also directly proportional to the pressure drop across the collection equipment. Pressure drop is the main parameter in determining the operating cost of the fabric filter system. The cost of bag replacement is second to the pressure drop costs, but they are related.

Low air-to-cloth ratios will lead to lower pressure drops across the filter and longer bag life, thus resulting in higher capital costs with lower operation and maintenance costs. On the other hand, higher air-to-cloth ratios will increase pressure drop, decrease bag life and possibly affect the reliability and availability of the collection system.

An optimum solution can be found. The choice must be based upon what the site specific need is and what the overall utility philosophy is. The following are considerations which should be incorporated in determining the air-to-cloth ratio:

- Determine the maximum amount of land area available for installing the fabric filter system. This is of major importance if the system is being retrofitted on an existing boiler unit. Installations at new power plant sites usually allow for more flexibility.
- Determine the maximum possible flue gas flow rate that can be emitted to the baghouse. This should include burning the fuel with the worst combustion characteristics that the boiler can handle; i.e. lowest BTU per pound, highest excess air, highest moisture content, etc. The calculation should also include leakage into the flue gas which would increase the flow rate such as air heater leakage, tempering air, soot blowing, etc. Air flows used for design purposes which are obtained from measuring the flow rates of existing units may be misleading. These flow rates are usually lower than the maximum and will more than likely result in higher air-to-cloth ratios and higher pressure drops than desired.
- Determine the maximum pressure drop that can be handled by the fans while maintaining maximum load while burning the fuel with characteristics likely to produce the most particulate.

Theory shows a relationship between pressure drop across the filter with respect to air-to-cloth ratio as follows:

$$P = Sv$$

Where: ΔP is the average pressure drop across the baghouse (inches of water),

v is the air-to-cloth ratio, (ft./min.),

S is the filter drag (inches of water/ft./min.)

Field measurements on a Colorado Springs system have shown a filter drag of approximately 2.5 inches of water/ft./min. (1) This is from fly ash from northwest Colorado coal in a pulverized coal boiler. The mass mean diameter of the fly ash particles ranged from 2 to 50 µm. (2) It should be noted that the ΔP calculated for all compartments in the filtering mode will not be the maximum pressure drop that will be used to design the fan. When compartments are in the cleaning mode or out of service for maintenance, the air-to-cloth ratio will increase, thus increasing the pressure drop.

If there is a strict size limitation due to available land area, the maximum size of the baghouse may already be determined. The determination to be made then is how many compartments should the baghouse have and what should the size of the fan be to move the air through the baghouse. Be careful of promises to provide low pressure differentials with high air-to-cloth ratios. This is contrary to the laws of physics. Such promises may lead to undersizing the fan, thus load limiting the boiler unit.

If land area is not a limiting factor, an optimum size can be determined by performing a cost analysis. Remember, a lower air-to-cloth ratio will increase capital costs by increasing materials and labor and a higher air-to-cloth ratio will increase operation and maintenance costs by increasing pressure drop across the system and reducing bag life. However, it is possible to run into operating problems if the air-to-cloth ratio is too low. If the velocity in a compartment is reduced and the temperature is low, which is typical of low load operation, moisture in the flue gas stream may condense in areas of no flow and begin corroding. It should be noted that maintaining a sufficient velocity in a compartment or in the ductwork will minimize if not eliminate condensation, even if the temperatures are below the dewpoint.

To give an example, the City of Colorado Springs has installed two fabric filter systems within the last two and a half years. One system was retrofitted on a 400,000 ACFM 85MW unit and the other was installed on a new 1,071,600 ACFM 200MW unit. Both systems were specified with the same conservative conceptual design parameters. Both fabric filter systems operate at an efficiency exceeding 99.9% at average pressure drops of approximately 4.5 inches of water, even though they are built by different vendors. The City did not issue a design specification, but instead it specified a performance contract, so each manufacturer was to use his best engineering practices considering the following conceptual parameters:

- An independent cleaning cycle operation was provided for nominally every 500,000 ACFM.

- The air-to-cloth ratio was 2:1 for each independent cleaning cycle with one compartment out of service and one compartment in the cleaning mode (two compartments out of service).

- The bag cloth area was defined to be the active filter area and shall not include surfaces occupied by anti-collapse rings, caps, cuffs, seams, or the length of the inlet thimble penetration.

- The maximum composite pressure drop across each baghouse module gas inlet and outlet manifold shall not exceed 5.0 inches of water gauge.

Both baghouse systems operate with similar results. Both exceed state and federal collection requirements by about 75%. Both systems have negligible maintenance cost and the system availability exceeds 99%. The 85MW unit has one clean cycle operation with twelve compartments and 198 bags thirty feet long and twelve inches in diameter in each compartment. The 200MW unit has two independent cleaning cycle operations. Its thirty-six compartments are housed in two modules of eighteen compartments each with 156 bags thirty-one feet long and 12 inches in diameter in each compartment.

Filter Cleaning Systems

During the filtering process, fly ash builds up on the inside of the fabric. The velocity through the fabric will remain constant, but the filter drag will increase, thus increasing pressure drop. In order to continue to operate the baghouse, without exceeding the capabilities of the fan in the system, the bags must be periodically cleaned. Systems utilized in cleaning the bags include reverse air, high pressure pulse, and shaking the bags.

It should be noted that the primary mechanism for cleaning the bags is mechanical action. That is, during the filtering process, the ash forms a "cake" on the inside wall of the bag. Changing the shape of the bag during the cleaning period will break this cake away from the bag wall and allow it to fall into the collection hopper.

Reverse air cleaning is one of the most widely used cleaning mechanisms. The filter bags are nominally 30 to 35 feet long and 12 inches in diameter with steel anti-collapse rings spaced throughout the length of the bag. When a compartment of bags is put in the cleaning mode, it is isolated from the flue gas stream, and clean hot flue gas enters the compartment in the reverse direction. This will collapse the bags, thus breaking off the filter cake. The anti-collapse rings will prevent this long bag from "pancaking" (collapsing to the point where the bag becomes flat thus not allowing the filter cake to fall into the storage hopper). The amount of reverse air used should be only as much as is needed to collapse the bags. Under normal conditions too much reverse air will tend to overclean the bags, thus reducing overall collection efficiency, and reducing bag life.

Shaking the bags is the second most widely used method for cleaning. The compartment is isolated from the flue gas stream, the bags are gently shaken and then subjected to a gentle reverse air flow. This will change the shape of the bags, which will then break the fly ash cake away from the wall of the bag. Bags in a shaker system do not have anti-collapse rings. With the shaking action, these rings will cause wear and premature failure. As a result, if the bag is too long, pancaking may occur. Experience in Australian baghouse applications indicates that a baghouse with a shaker type cleaning method should not have bags exceeding 20 feet in length and six inches in diameter (3). This will result in an effective cloth area per bag about one third of that for a bag used in a reverse air cleaning system. For the same air-to-cloth ratio, this will result in a baghouse structure taking up at least three times the ground area. Utilizing larger bags in the shaker cleaning type baghouse will result in less efficient cleaning which will increase the filter drag, thus increasing pressure differential across the system.

High pressure pulse cleaning is limited by the size of the filter bags. The compressed air used to emit the pulse to the bag is only effective to bags up to approximately 15 feet long. Pulse jet baghouses are generally designed at an air-to-cloth ratio approximately twice that of reverse air or shaker baghouses. Even so, a pulse jet would require twice the land area of a reverse air type baghouse. The pulse jet tends to overclean the bags which will increase emissions. On the average, reverse air type baghouses have offered the most cost effective operation on large utility boilers to date.

Bag Specifications

The typical fabric used in constructing the fabric filter bags for use on coal-fired boilers is fiber glass. With the recent introduction of spray absorbtion techniques for flue gas desulfurization, inlet baghouse temperatures will be lower. This will lead to use of other types of fabrics being used in fabric filter collection systems. It should be noted that if low temperature fabrics are used in installations following spray absorbtion systems, the availability of the boiler unit may be lowered. If there is a malfunction with the spray absorber unit, the entire boiler and baghouse unit will have to be shut down until the malfunction is corrected. The low temperature bags will not be able to withstand the higher temperatures resulting from a spray absorber which has been bypassed.

Varying finishes are available with fiber glass bags to prevent self-abrasion of the fiber glass. Some typical finishes include teflon, silicon graphite, and a tri-coating which uses a combination of teflon, silicon graphite and an acid resistant coating. The finish specified is to the customer's preference. An investigation should be conducted on the desirable bag performance and baglife characteristics before specifying and accepting a particular bag finish from a vendor.

The bag specification should include the number and type of anti-collapse rings if the baghouse incorporates a reverse air cleaning system. A typical specification for anti-collapse rings may be as follows:

> Bags shall be provided with a minimum of seven sewn-in anti-collapse rings (bags nominally 30 feet long and 12 inches in diameter). The rings shall be 3/16 inches minimum thickness steel located 30 inches from the bottom of the bag and on four centers.

It should also be specified that the top end of the bag be provided with a steel cap with an eye bolt (4). It is advisable to specify stainless steel rings and caps to minimize deterioration due to the corrosive flue gas environment.

The bags provide the collection mechanism of the system. Special attention should be given to their selection. The proper bag given the proper care will lead to a highly efficient cost-effective collection system.

Compartment, Hopper, and Inlet and Outlet Arrangements

The arrangement of the compartment and hoppers will more than likely be dictated by the space available for the installation. However, the arrangement of the inlet manifold and the inlets and outlets to the compartments are crucial to a cost effective operation.

The inlet manifold should be designed to approach an equal distribution of particles to each compartment. The inlet to the hopper area and outlet of the compartment should be located to provide an equal distribution of flow to all the bags. Also, the velocities entering and leaving a compartment should be low enough not to cause turbulent flow in the hopper area. Turbulence will cause increased pressure drop and decrease the effective cloth area of a compartment. Typical velocities entering a compartment which will reduce turbulence are 20 to 25 feet per second. The typical outlet velocity range is from 30 to 40 feet per second.

It is advisable to require a fluid flow model study in the specification to arrive at the proper arrangement to maximize the effectiveness of the fabric filter system.

Operation Control Systems

The type of logic control system is again a matter of customer preference. New microprocessor control systems provide more flexibility, are easier to reprogram and utilize approximately one-one hundredth of the space of the relay-time type logic control systems. Ease of trouble shooting and longer component life are also advantageous to the microprocessor controllers.

If a pneumatic actuator system is used, the following should be provided to insure a reliable operation:

- A sufficiently sized air dryer to eliminate moisture in the system which could freeze in cold weather or cause corrosion in the system.

- A sufficiently sized air receiver to provide quick recovery of the air supply system following an emergency bypass and isolation situation.

- Air regulators and lubricators at each pneumatic operator to provide consistent reliable service.

Some instrumentation which will be useful during start-up and operation of a fabric filter system includes:

- Inlet and outlet temperature recorders.
- Individual compartment temperature recorders.
- Flange to flange pressure drop recorder.
- Inlet flow rate recorder.
- Reverse air flow rate recorders.
- Visual emissions monitor recorder.
- Compartment operational mode indicators.

Bypass and Emergency Control Provisions

Many new installations provide for a baghouse bypass which is used during start-up of a boiler unit and for emergency isolation during a serious boiler system upset condition. The bypass must be designed so that there is no leakage of dirty flue gas to the stack during normal operation. A typical way to avoid leakage is to provide a double louvre damper system in the bypass duct work. The plenum between the louvre dampers is then pressurized with a seal air fan or a globe valve so that leakage is from the plenum to the bypass duct work in both directions, thus eliminating fly ash infiltration around the baghouse.

The baghouse bypass is an advantage during the start-up period of the boiler unit. It allows the boiler to be started up and stabilized on clean fuels, such as natural gas and No. 2 fuel oil. The baghouse can then be put on-line with hot flue gas from these fuels just before going to coal firing. This will minimize the potential for condensation forming during the initial start-up stages which could lead to blinding the bags.

Emergency bypass and isolation operations should be provided to prevent irreparable damage during certain upset conditions. Such conditions would probably lead to boiler unit shutdown so, in these cases, system protection is essential. Emergency conditions of great concern are excessive differential pressure across the baghouse and high temperatures entering the baghouse. High differential pressure can be caused by a massive boiler tube leak. High inlet temperatures can be caused by a malfunctioning air preheater. Both situations will result in damage to the bags if not isolated. Also, these emergency situations will cause a boiler shutdown; therefore, continued exceedences of emission standards are unlikely.

A low temperature bypass trip, which has been used in some baghouse installations is unnecessary. In fact, it may cause more harm than good. The only time a low temperature situation arises is during a controlled shutdown. If warm moisture laden flue gas is isolated in a bypassed baghouse during the shutdown process, these stagnated gases will slowly cool down in the compartments and the moisture will condense on the compartment walls and the bags. This will result in corrosion of the compartment walls and operating valves. The condensed moisture will also form small nodules with the ash increasing filter drag, thus resulting in higher operating pressure drops.

If low load operation results in dangerously low baghouse inlet temperatures, an air preheated bypass can be provided to increase the temperature to the baghouse.

If the baghouse is bypassed and isolated as a result of an upset condition, provisions should be made in the operating instructions to purge the baghouse of the moisture laden flue gases. Ambient air contains less than one-tenth of the moisture than flue gas.

Other Options

With the introduction of dry FGD systems preceding a fabric filter system, inlet temperatures to baghouses are lower. A spray absorbtion system reduces sulfur content of the flue gas. Acids resulting from carbon dioxide and oxides of nitrogen can be formed at temperatures approaching adiabatic saturation of the flue gas. During full load situations when compartment velocities are their highest, the probability of low pH condensation is minimal. However, at reduced load situations when air-to-cloth ratios are lowered, acidic condensation may develop. Therefore, it is advisable to investigate reheat systems which will meet the need of the specific boiler unit.

Some fabric filter installations have incorporated a preheat system to prevent moisture condensation during start-up and shutdown. This is an expensive luxury which can be avoided by developing and implementing good start-up, shutdown and operating procedures. This is possible even for a cycling unit.

Operation and Maintenance Instructions

The specifications should require detailed operation and maintenance instructions not only for the entire system as a whole, but also for individual components. These instructions should include trouble shooting procedures, periodic component checks, calibration procedures and procedures for start-up, shutdown, and emergency contingencies.

The start-up and shutdown procedures are of particular importance. These procedures are unique to each installation and must be customized. They must be incorporated in the boiler and turbine start-up and shutdown procedures. Because of environmental restrictions, the fabric filter system has become an integral part of coal-firing to produce electricity. These procedures are as important as the components of the baghouse for properly operating the system.

Guarantees and Warranties

The best specification that can be written will state the desired results and allow the vendor to utilize his expertise in designing and installing his product. Unfortunately, the process of competitive bidding may short circuit this ideal. As a result, a specification must be written to obtain the desired results without inhibiting the vendor's talent and expertise. This is commonly referred to as a performance specification.

A performance specification should be based upon rendering final compensation to the vendor in return for specific performance criteria. The criteria should be based on results. These results should reflect economics, operationability, and compliance with applicable environmental standards. Therefore, criteria for achieving the desired performance must be specific. Examples of performance criteria are:

- Maximum pressure drop across the fabric filter system.

- Maximum temperature drop across the fabric filter system.

- Minimum acceptable collection efficiency under specified operating conditions of the baghouse.

All tests performed to prove compliance with the performance criteria must be specific and relative to the purpose of the operation of the entire system within the constraints of environmental standards.

Design Input to Vendors

In order to obtain what is needed for particulate control, the proper input must be provided to the vendor. This again will be unique to each specific application. The following is a suggested list of parameters which will facilitate the design and installation of the equipment to meet your needs:

- Size and type of combustion unit.
- Primary fuel and ignition fuel.
- Static pressure at baghouse inlet.
- Expected flue gas temperature at full load and maximum load.
- Maximum flue gas temperature.
- Maximul fuel firing rate.
- Flue gas flow rate at maximum load and minimum load.
- Coal analysis to include moisture content, sulfur content, ash content, and heat rate in BTU/lb.
- Maximum fly ash rate to baghouse.
- Elevation at plant site.
- Flue gas temperature for equipment selection and structural design.
- Snow loads, wind loads, and seismic loads.
- Internal pressure design.
- Fly ash density.
- Minimum fly ash storage capacity.
- Dust load build-up conditions in ductwork.
- Maximum acceptable pressure and temperature drop across system.
- Bag specifications including bag reach.
- Maximum velocity through each compartment inlet and outlet.
- Maximum air-to-cloth ratio.
- Installation space limitations.
- Model study results.
- Calculations deriving air-to-cloth ratio with respect to pressure drop, damper leakage, thermal movement, temperature differential throughout the system, hopper sizing.

Conclusion

A fabric filter has proven to be a very cost-effective means to obtain high collection efficiency of particulates produced by utility boilers. These systems, if properly designed and operated, can provide a means of controlling particulate emissions with high availability with reasonable operating and maintenance costs. The operation of a fabric filtration system is not complicated. Specifying such a system can be equally as uncomplicated by determining the specific need and results required.

ENDNOTES

1. Test Report for Research and Development on Test Baghouse at Martin Drake Unit No. 6, City of Colorado Springs, Volume II, Mathematical Modeling, Eric A. Samuel, 1980.

2. Test Report for Research and Development on Test Baghouse at Martin Drake Unit No. 6, City of Colorado Springs, Volume II, Main Baghouse and Pilot R & D Baghouse Particle Loading, T. K. Chiang, 1980.

3. Discussion with Electricity Commission of New South Wales, Sidney, Australia, February 9, 1981.

4. Specifications for Modular Baghouse Fabric Filter System for the Ray D. Nixon Power Plant, 1976.

EVALUATION OF THE 25 MW KRAMER STATION BAGHOUSE: OPERATIONAL FACTORS IN PARTICULATE MATTER EMISSION CONTROL

By

R. C. Carr
M. W. McElroy

Electric Power Research Institute
Palo Alto, California

The Electric Power Research Institute (EPRI) is currently supporting a major research program characterizing the emission control performance of fabric filter baghouses in coal-fired utility boiler applications. One such effort reported here is an evaluation of the Kramer Station baghouses of the Nebraska Public Power District. These units represent the first application of fabric filter control technology to pulverized-coal fired utility boilers burning a western, low-sulfur sub-bituminous coal.

As summarized below and in Figure 1, the baghouse cleaning cycle had the greatest effect on particulate matter removal efficiency compared to any other operational parameters. Implementation of a "preferred" 100-minute cleaning cycle, obtained by extending the dwell time between compartment cleaning from zero to eight minutes, reduced particulate matter penetration by 50 percent without an increase in pressure drop. Total particulate matter collection efficiency measured for the baghouse with the preferred cycle in effect averaged 99.92 percent, with associated outlet emissions and stack opacity of 0.001 lb/10^6 Btu (0.43 ng/J) and 0.07 percent, respectively. The 0.07 percent opacity is equivalent to a 20 kilometer stack "visibility." As shown in Figure 2, the baghouse size dependent mass collection efficiency exceeded 99 percent over the measured 0.02 to 10 micrometers diameter size range. The clear stack and low outlet emissions were maintained throughout the nine-month test program despite intentional variations in baghouse operating parameters and uncontrolled fluctuations in coal ash content and boiler combustion conditions. The continuing good performance during these episodes suggests that the baghouse is a very effective and forgiving particulate emission control device for utility application. The particulate mass removal efficiencies and outlet emissions measured for Kramer are remarkably similar to results obtained in a previous EPRI study of the Nucla Station baghouse. This comparison is very significant since there are major design differences between the two baghouse installations and boilers (Nucla is spreader-stoker whereas the Kramer units are pulverized-coal).

KRAMER UNIT 3 BAGHOUSE EMISSION SUMMARY

Cleaning Cycle	*Air/Cloth Ratio (acfm/ft^2)*	*Average Concentration (gr/scf)*		*Efficiency (%)*	*Opacity (%)*	*Emissions (lb/10^6 Btu)*	
		Inlet	*Outlet*			*Total*	*< 2 μm*
Continuous, 10-minute cycle	1.80	1.00	0.0014	99.86	0.08	0.002	0.0005
Preferred, 100-minute cycle	1.86	0.69	0.0006	99.92	0.07	0.0009	0.0002
No cleaning, 350 minutes	1.57	1.38	0.00032	99.98	0.02	0.0005	0.00008

Figure 1

OUTLET CONCENTRATION VS AIR-TO-CLOTH RATIO

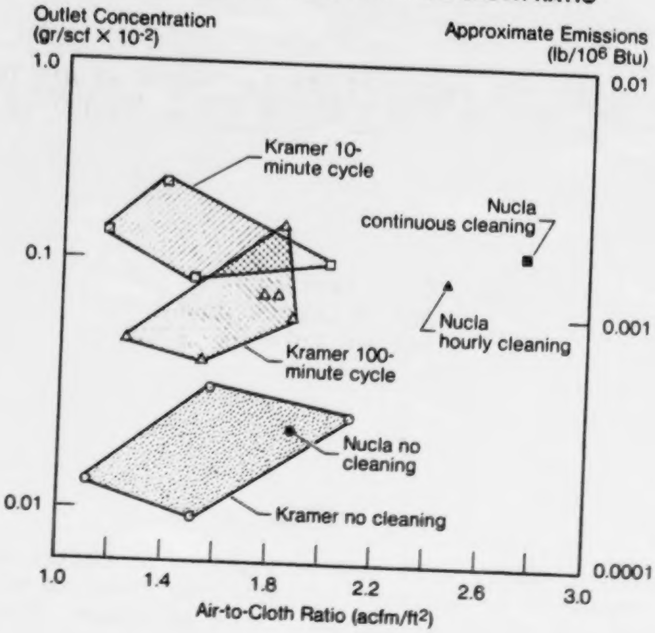
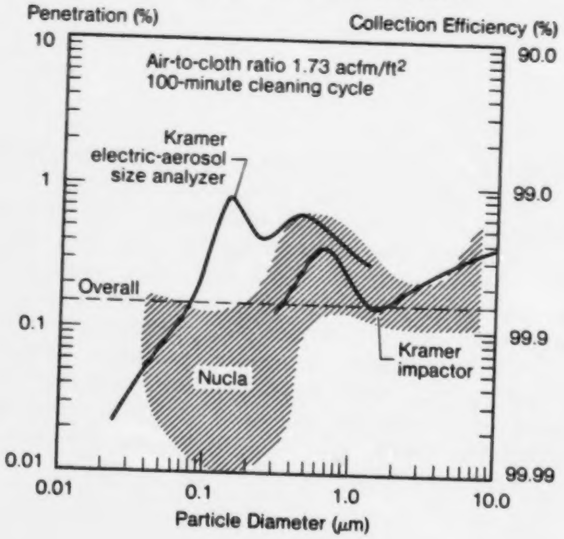


Figure 2

SIZE DEPENDENT PENETRATION



PULSE-JET TYPE FABRIC FILTER EXPERIENCE AT AIR TO CLOTH RATIOS OF 5 TO 1 ON A BOILER FIRING PULVERIZED COAL

By: G. L. Pearson
Adolph Coors Company
Golden, Colorado 80401

ABSTRACT

Since November, 1979, a 12 module baghouse of Carter-Day design has been in operation successfully controlling emissions from the Boiler No. 5 pulverized coal fired unit rated at 450,000 LB/HR of steam. Bags are made of 22-ounce felted "Ryton" and cleaning is accomplished only as required via a low pressure-moderate volume, pulse-jet technique.

This paper describes the system and covers the operating experiences with this installation during the first 15 months of operation. Data on outlet particulate emissions, pressure drop, and cleaning cycles is presented.

INTRODUCTION

Energy availability considerations and cost projections motivated Coors to proceed with their second coal fired boiler (Unit No. 5) in late 1976. This unit was scheduled for start-up and went into service in November, 1979. In the installation of this coal fired boiler, it was important to the Company that not only permit requirements were met, but that emissions were minimized to the lowest levels possible with current technology. However, both space and capital dollars were at a premium to accomplish these objectives. After study and careful consideration, a pulse-jet type modular system, offered by Carter-Day of Minneapolis, was selected to control particulate emissions. This modular system was ordered in April, 1978, and went into service with the boiler in November, 1979. It has operated successfully for the last 15 months.

BOILER DESCRIPTION

The boiler is a Combustion Engineering pulverized coal VU-40 type unit rated at 450,000 LB/HR of steam at 825 PSIG and 850°F. Coal is pulverized with three Raymond RB-613 bowl mills. A large fin tube boiler feedwater economizer is utilized to cool the flue gas to within the temperature range of 300°F to 360°F depending upon boiler load. The boiler was designed for, and operates with, a 3 to 1 turn-down capability.

BAGHOUSE MODULE DESCRIPTION

The basic configuration of the Carter-Day Model 376 RF10 high temperature unit is illustrated in Figure 1. Each circular unit has 376 oval pattern bags, 10 feet long for a filter area of 4800 sq. ft. per module. (The 12 module system has 4512 bags and a filter area of 57,600 sq. ft.) Bags are installed over and supported by carbon steel 9-gauge wire frame cages. Fly-ash cake is accumulated on the outside of the bags and the filtered flue gas leaves at the top of the units and goes to the induced draft fan and stack. Bags are installed or removed through the top clam shell doors at the top of the units.

Bags are made of 22-ounce per square yard "Daytex" felted fabric. This fabric is essentially felted and needled "Ryton" fibers on a "Gortex" scrim. "Ryton" is the trademark name which Phillips Petroleum has given to Polyphenylene Sulfide. This material has both excellent acid resistance and temperature resistant characteristics up to 370°F.

Cleaning of the filter cake from the outside of the bags is accomplished by opening the diaphragm valve at the top of the unit and discharging the 7.5 PSIG reservoir tank into the inside of the bags directly under the nozzles on the distribution manifold. Each reservoir tank is charged to 7.5 PSIG by a Miehle-Dexter Model Number 46-4006 positive displacement blower. Since each module has its own blower, tank, valve, etc., the reliability of the overall system is quite good. Tripping of the diaphragm valve is signaled by a pressure switch mounted on the reservoir tank. The distribution manifold is turned at one rotation per minute during cleaning via a small ½ HP motor and gear box to the side of the diaphragm valve. When in the cleaning mode, the diaphragm valve pulses approximately every 3.7 seconds.

BAGHOUSE INSTALLATION AND AUXILIARIES

To insure a good, economical and easy to operate and maintain system, considerable thought and engineering went into the installation. Figures 2 and 3 show the basic module installation configuration. The inlet and outlet plenums were designed to balance the distribution to each module and keep the ductwork free of ash drifts. In order to minimize troublesome and expensive expansion joints, all modules and some flue ducts are supported by hanging rods which allow adequate movement due to thermal expansion. The entire system has only 10 expansion joints. Each module has a minimum leakage type outlet damper, which can be operated remotely from the control room to either take a module off-line or to accomplish off-line cleaning. When this damper

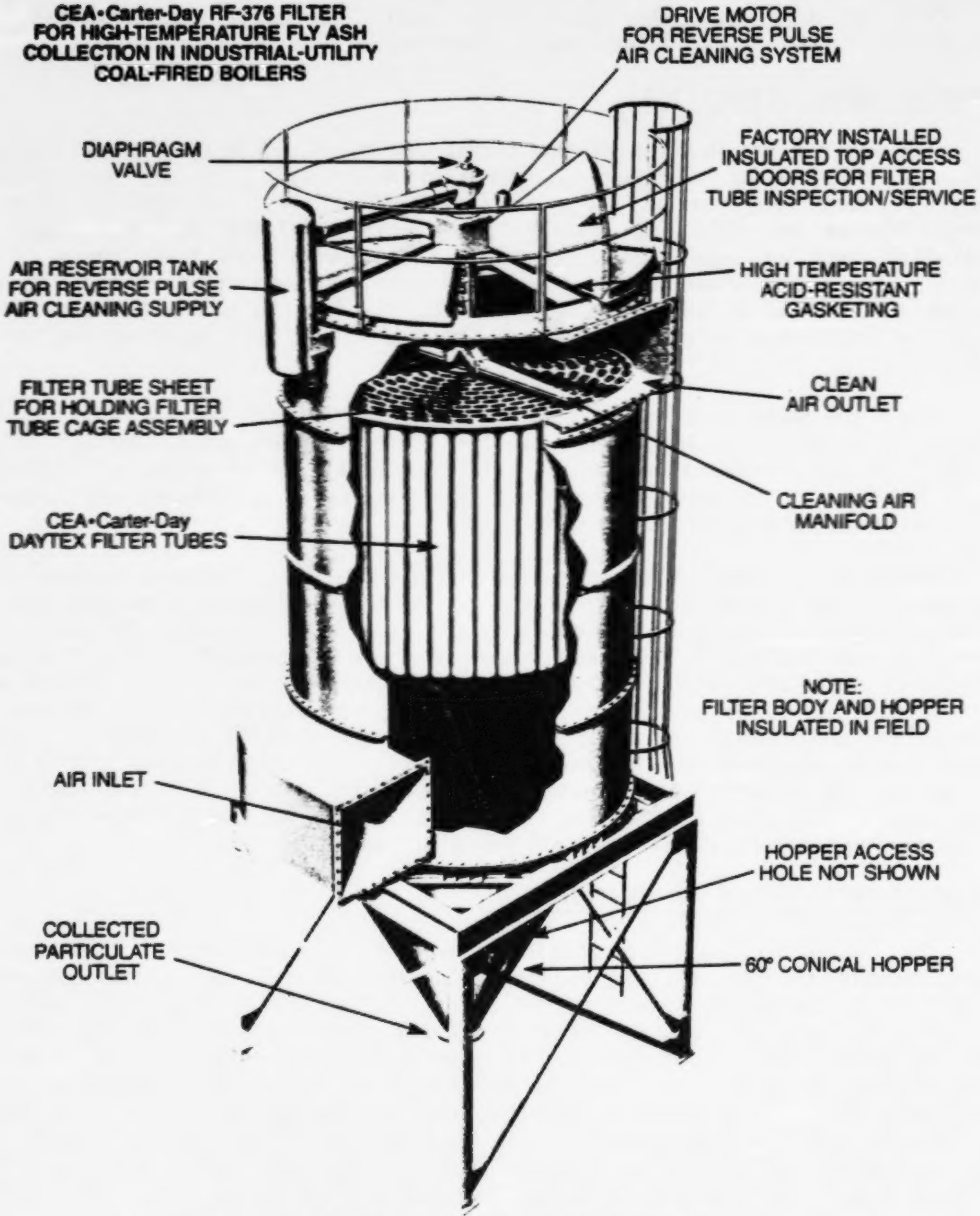

CEA•Carter-Day RF-376 FILTER FOR HIGH-TEMPERATURE FLY ASH COLLECTION IN INDUSTRIAL-UTILITY COAL-FIRED BOILERS
DRIVE MOTOR FOR REVERSE PULSE AIR CLEANING SYSTEM
DIAPHRAGM VALVE
FACTORY INSTALLED INSULATED TOP ACCESS DOORS FOR FILTER TUBE INSPECTION/SERVICE
AIR RESERVOIR TANK FOR REVERSE PULSE AIR CLEANING SUPPLY
HIGH TEMPERATURE ACID-RESISTANT GASKETING
FILTER TUBE SHEET FOR HOLDING FILTER TUBE CAGE ASSEMBLY
CLEAN AIR OUTLET
CLEANING AIR MANIFOLD
CEA•Carter-Day DAYTEX FILTER TUBES
NOTE: FILTER BODY AND HOPPER INSULATED IN FIELD
AIR INLET
HOPPER ACCESS HOLE NOT SHOWN
COLLECTED PARTICULATE OUTLET
60° CONICAL HOPPER

FIGURE 1 MODULE GENERAL CONFIGURATION

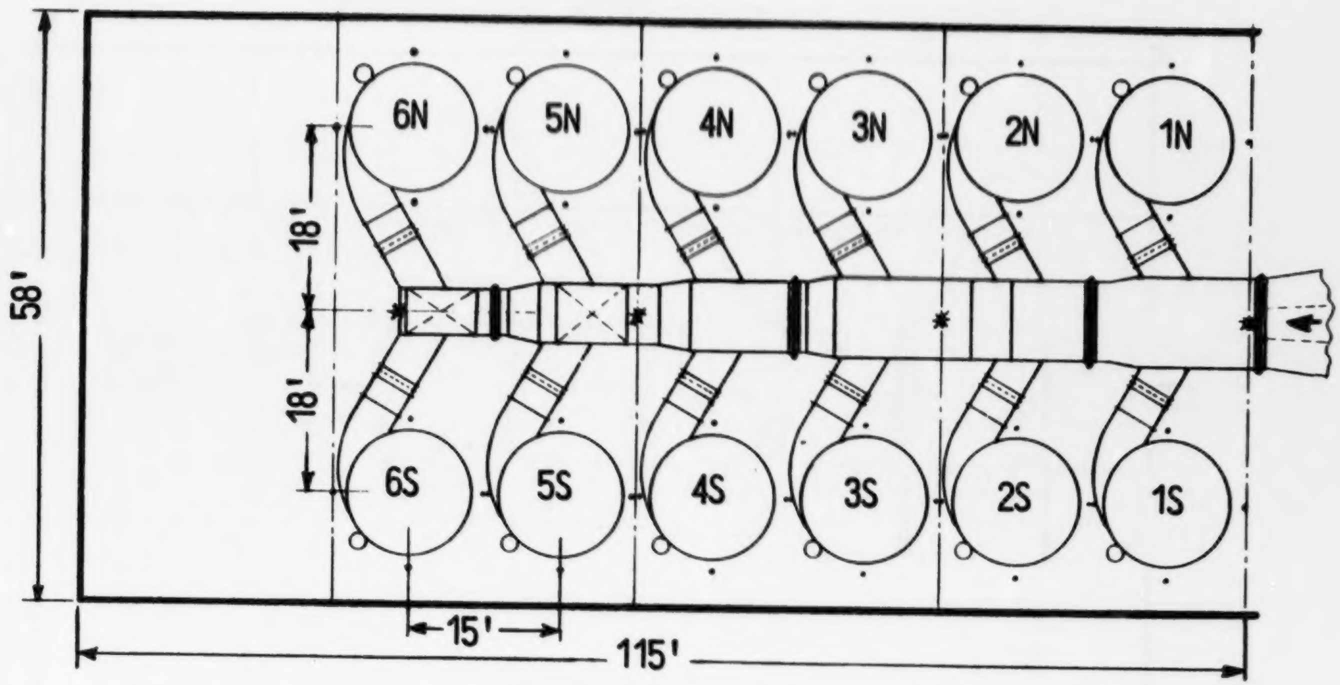

6N
5N
4N
3N
2N
1N
6S
5S
4S
3S
2S
1S
18'
18'
58'
15'
115'

FIGURE 2 PLAN VIEW OF MODULE ARRANGEMENT ILLUSTRATING INLET PLENUM

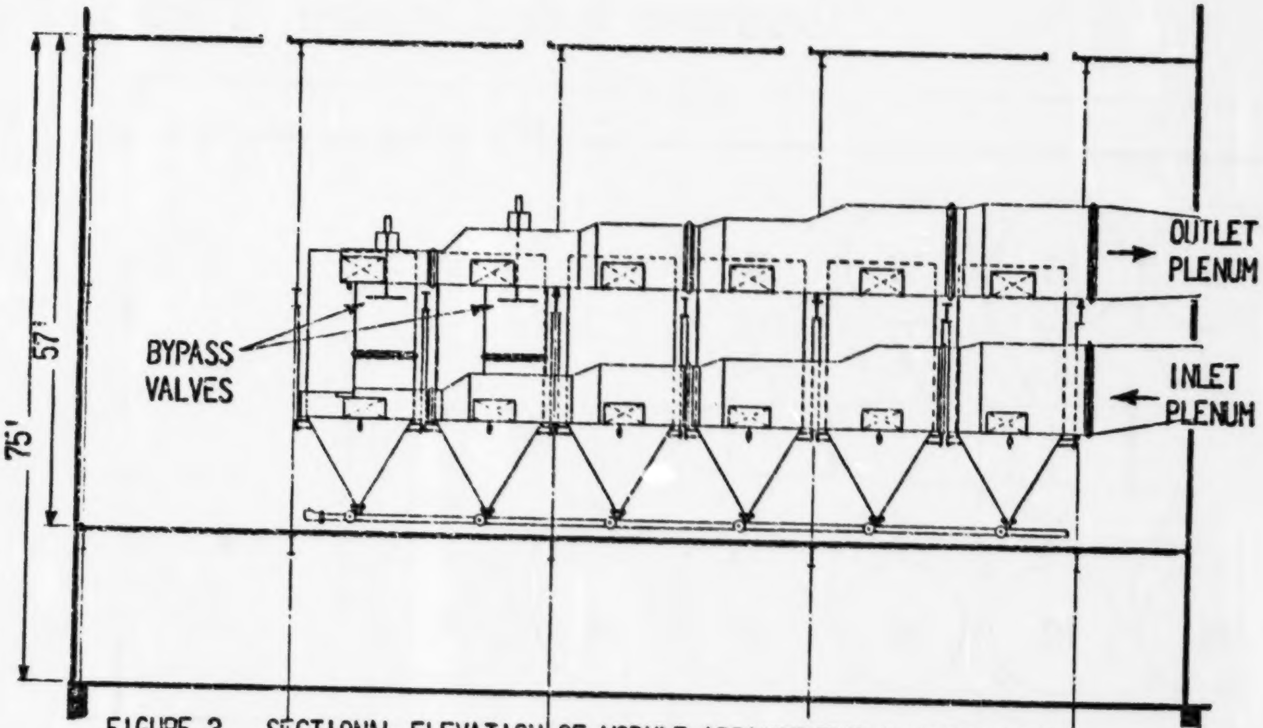

75'
57'
BYPASS VALVES
OUTLET PLENUM
INLET PLENUM

FIGURE 3 SECTIONAL ELEVATION OF MODULE ARRANGEMENT ILLUSTRATING BY-PASS VALVES, INLET PLENUM, OUTLET PLENUM, MODULE SUPPORT RODS, AND CONFIGURATION OF BUILDING ENCLOSURE.

is closed, a small valve at the top of the unit opens, automatically letting air in to purge that particular module and prevent acid corrosion. Each module is equipped with a manually operated inlet damper for use when that module is in a maintenance mode. There are two 60-inch diameter bypass poppet type valves in the system which are used during start-up and oil firing of the boiler. These bypass valves are operated from the control room and can open against 40 inches W.G. pressure.

The conical ash hoppers are insulated with 10 inches of MT-8 mineral wool insulation and electric blanket heaters are used on the bottom 3'-6" portion of the cone to insure that the flyash will stay dry and convey easily. The main portion of the module and all flue ducts are insulated with 4 inches of MT-8 mineral wool insulation. The modules and flue ducts were metal lagged with "Reynolds Rainlock Rib" diamond embossed aluminum 0.0165 inches thick. The conical hoppers, and other difficult areas, were lagged with flat diamond embossed aluminum 0.025 inches thick. High ash level alarms are installed in each hopper.

Because of the location of the facility (adjacent to the main entrance and visitors area of the plant), an enclosure was built for the facility to satisfy aesthetic considerations. This enclosure is shown in Figures 2 and 3.

An opacity meter (Lear Siegler RM-41) is installed in the 13 foot diameter stack downstream of the baghouse and induced draft fan. Readout of opacity in the control room is located so as to be easily visible from the baghouse operator panel.

The operator panel for the baghouse, located in the control room, has the following features:

1. Pressure drop across the baghouse (inlet plenum to outlet plenum) is displayed on a meter. The operator can select the high pressure that he wants cleaning to start at and the low pressure where he wants cleaning to cease on this meter.
2. Temperature of the flue gas going to the baghouse is displayed on a meter on the control panel.
3. Conditions of either high baghouse pressure drop or high temperature are alarmed via red lights and buzzers.
4. The module outlet dampers can be either closed or opened from this panel to isolate a module or accomplish off-line cleaning. Damper position is indicated by status lights.
5. Bypass valves can be opened or closed from this panel. Status lights indicate their location at all times.
6. The status of which modules are in the clean mode is indicated on this panel to the operator via blower motor running status lights.

The total installed turn-key cost of this 12 module system, including the enclosure building, was approximately $2,500,000, or roughly $8 per design ACFM.

BAG CLEANING CYCLE LOGIC

During the design phase, Coors engineers and Carter-Day engineers mutually agreed to set up the system so that normally, cleaning would be accomplished only as needed to enhance bag life, blower life, and to save energy. The blower and manifold turning mechanism motors on all modules would come on when the pressure across the baghouse reached the high set point (for example, 5 in. W.G.). The modules would be in the clean mode until the pressure drop across the baghouse reached the lower set point (for example, 2 in. W.G.) and cleaning would cease until the pressure built up to the high set point again. Shortly after start-up, this was found to not be very practical because the cleaning was so effective that the pressure drop across the baghouse would drop from 5 in. W.G. to 2 in. W.G. in only 20 to 30 seconds and the stack opacity became higher than desirable for a short period of time.

To reduce the effect of this problem and to insure that nearly all bags get pulsed when a module is cleaned, the PLC (programmable logic computer) software was changed to clean only 4 modules at a time and run the clean mechanism for 5 minutes at a time. Using this scheme, 8 modules are always in the passive no-clean mode. The four modules cleaned are sequentially stepped by the software so that each module gets the same number of 5 minute clean cycles over a period of time. This cleaning method on a demand basis has worked well over the current operating range of the boiler (150,000 LB/HR to 400,000 LB/HR of steam). Generally, the baghouse is in the no clean mode with none of the 12 clean blowers running 50% to 70% of the time.

EMISSION TESTS

Emission tests were performed at the stack of this unit on April 17 and April 18, 1980, as part of the Compliance Tests required on the permit for this coal fired boiler. The results of the EPA Method No. 5 particulate tests are shown in Figure 4. The average of the three tests via F Factor method is .023 LB per million BTU particulate (roughly ¼ of the permit requirements.) Since this ratio is energy rate dependent, data is also presented with respect to the energy bases of steam rate out and coal consumed.

The coal burned during the compliance tests had a heating value of 10,700 BTU per LB., a moisture content of 13.64%, an ash content of 5.89%, and a sulfur content of 0.53%, all on an as-received basis. This coal comes from Routt County, Colorado.

During operation of this unit, the plume has been essentially non-visible day-in and day-out to a human observer.

COMPLIANCE TESTS ON BOILER NO. 5
ADOLPH COORS COMPANY
(DATA PER EPA METHOD NO. 5)

	TEST #1 4-17-80 1200-1355	TEST #2 4-18-80 0902-1047	TEST #3 4-18-80 1240-1424	AVG. OF 3 TESTS
PARTICULATE EMISSION RATE (BASED ON F FACTOR)	0.019 $\frac{LB}{10^{6}BTU}$	0.031 $\frac{LB}{10^{6}BTU}$	0.018 $\frac{LB}{10^{6}BTU}$	.023 $\frac{LB}{10^{6}BTU}$
PARTICULATE EMISSION RATE (BASED ON STEAM RATE)	0.018 $\frac{LB}{10^{6}BTU}$	0.029 $\frac{LB}{10^{6}BTU}$	0.016 $\frac{LB}{10^{6}BTU}$	.021 $\frac{LB}{10^{6}BTU}$
PARTICULATE EMISSION RATE (BASED ON COAL RATE)	0.019 $\frac{LB}{10^{6}BTU}$	0.021 $\frac{LB}{10^{6}BTU}$	0.016 $\frac{LB}{10^{6}BTU}$	.019 $\frac{LB}{10^{6}BTU}$
BOILER STEAM OUTPUT	405,000 $\frac{LB}{HR}$	420,000 $\frac{LB}{HR}$	420,000 $\frac{LB}{HR}$	
ACTUAL VOLUME OF FLUE GAS THRU FILTER	276,000 ACFM	293,000 ACFM	288,000 ACFM	
AIR TO CLOTH RATIO	4.79	5.08	5.00	

FIGURE 4 EMISSION TEST RESULTS

SUMMARY OF EXPERIENCE WITH SYSTEM

During the first 15 months of operation, this system has operated very well and up to expectations. All felted "Ryton" bags have maintained their integrity and there have been no bag failures. All mechanical components have functioned without failure or repair except for a few cases with the diaphragm valves. On a few occasions, they would stick and require some minor repair, which generally consisted of replacing the coil spring in the valve and adjusting it. This was accomplished by the boiler operator on duty in about 10 minutes.

The clean only-as-required and clean only 4 modules at a time (1/3 of the 12 modules) has generally worked well throughout the current normal operating range of the boiler (150,000 LB/HR to 400,000 LB/HR), maintaining the pressure drop across the baghouse within the range of 2.5 to 5 inches W.G.. Through experience, it has been found that operation at a pressure drop greater than 6 inches W.G. causes fine flyash to be driven through the felted "Ryton" causing a higher than desired opacity. It has also been learned that at air-to-cloth ratios, slightly above approximately 5 to 1, on-line cleaning is not effective over a long period of time in cleaning and discharging the flyash from the bags because of reintrainment of fine flyash. This reintrainment causes the pressure drop across the baghouse to gradually increase. Operation at higher than roughly 5 to 1 air to cloth ratios or recovery from a high pressure drop requires occasional off-line cleaning. Currently, this is done by the boiler operator in the control room by closing the module outlet damper during cleaning. Eventually, we plan to incorporate this feature automatically via software logic in the PLC computer. These techniques have worked quite well in bringing the baghouse back into an acceptable pressure drop range without taking any other corrective action such as reducing boiler load.

02/13/81
re/2U

SELECTION AND OPERATION OF BAGHOUSES AT R. D. NIXON STATION, UNIT #1

By: R. C. Hyde
JOY Manufacturing Company
4565 Colorado Boulevard
Los Angeles, California 90039

J. Arello
Lutz, Daily & Brain, Consulting Engineers
6400 Glenwood
Overland Park, Kansas 66204

D. J. Huber
City of Colorado Springs
Ray D. Nixon Power Plant
Fountain, Colorado 80817

ABSTRACT

This paper discusses the selection criteria and the subsequent successful operation of two (2) baghouses placed in service at the R. D. Nixon Station, Unit #1. These baghouses serve one (1) 220 MW boiler and have been in continuous service since April, 1980.

This paper identifies the specification criteria deemed most important for a successful baghouse installation and reviews the architect's decision-making process in selection of this type of air pollution control equipment. Results from the first eight (8) months of operation are presented including pressure drop, opacity, outlet emission, etc.

To date, the unit has operated with low outlet emissions and low pressure drop (3-4 inches, W.C.). Additionally, start-up, shut-down, and maintenance procedures are discussed.

INTRODUCTION

Forecasted load growth and replacement of retired generating units required that the City of Colorado Springs, Colorado install additional electrical generating capacity. On April 4, 1980, the Ray D. Nixon Power Plant, Unit #1, located in Fountain, Colorado, some 17 miles south of Colorado Springs, began commercial production of 220 MW of electrical energy. The power plant design engineering was undertaken by Lutz, Daily & Brain. Equipment located at the plant includes a Babcock & Wilcox 1,450,000 pounds per hour steam generator, General Electric 220 MW turbine generator and a JOY Manufacturing Company "THERM-O-FLEX" baghouse system.

AIR POLLUTION CONTROL CONSIDERATIONS

The steam generator purchased by the City of Colorado Springs was a balanced draft, pulverized coal fired unit. The unit was designed to burn a low sulfur Western coal with a typical coal and ash composition as follows:

Coal Analysis, %		Ash Analysis, %	
Moisture	28.11	Phosphorus	0.85
Carbon	50.19	Silica	29.83
Hydrogen	3.54	Ferric oxide	4.88
Nitrogen	0.67	Alumina	15.75
Chlorine	0.01	Titania	1.18
Sulfur	0.32	Lime	23.52
Ash	4.87	Magnesia	5.00
Oxygen	12.29	Sulfur trioxide	15.31
		Potassium oxide	0.35
		Sodium oxide	1.09
		Undetermined	2.24

When the Utility used a low sulfur Western fuel and acquired an Environmental Construction Permit prior to the enactment of a more stringent state sulfur dioxide requirement, the installation of a wet scrubber was averted. However, it was recognized that a reliable and efficient particulate collection device would be required in order to operate within compliance of the newly adopted New Source Performance Standards. This meant a reduction in outlet emissions to a value no greater than 0.1 lb per million Btu heat input. It was also felt that although the requirements for sulfur dioxide removal were forestalled, the ever-changing regulations may dictate installation at a later date. A design philosophy was therefore established. An efficient particulate removal system would be specified and provisions for incorporation of sulfur dioxide removal equipment would be made.

The state of the art in particulate removal for low sulfur Western coal during the period in which the R.D. Nixon Station was in design was either a hot side precipitator or a gas conditioned cold side unit. However, the Utility's experience with both of these particulate control devices at the Martin Drake Station spawned interest in an investigation of a fabric filter collector, more commonly referred to as a baghouse. Little was known of this newcomer to the utility industry and a careful review of the few utility installations was made. After an exhaustive study, most of the skepticism concerning the use of the fabric filter subsided and a decision was made to issue two separate sets of design specifications. One set would incorporate the installation of a hot side electrostatic precipitator on which the utility had experience, and the other set of specifications would be for a fabric filter collector. Both sets of specifications announced the intent that bids were being taken for both a hot side precipitator and a baghouse, only one of which would be purchased by the Utility after a through evaluation.

BAGHOUSE SPECIFICATIONS

As a review was made into the possible operating parameters the baghouse would encounter, a specification started to evolve. The filter materials must be capable of withstanding the flue gas temperatures encountered including excursions. This entailed the use of fiberglass filtering material. In order to reduce wear during cleaning a reverse gas cleaning system in lieu of a shaker or pulse jet was specified. Coupled with the reverse gas cleaning system, came the decision that the ratio of gas volume to cloth area should be kept low in an effort to extend the time between cleaning cycles, thereby increasing bag life. This would have an additional benefit of an overall reduced pressure drop.

After reviewing the various air-to-cloth ratios and their relationships to the baghouse size and cost, a 1.9:1 gross air-to-cloth ratio was chosen. In recognizing the size and possible problems with one unit, a minimum of two baghouse units would be required. To keep the unit operational at a conservative air-to-cloth ratio during periods of compartment cleaning or maintenance, the air-to-cloth ratio was specified to not exceed 2.1:1 during a period of two compartments off-line. This required more compartmentalization but insured that enough bag material would be available for safe operation.

In an attempt to provide a safe and dependable system, other features incorporated into the specification included a compartment door interlock system which prevented unauthorized entrance and weather protection by hopper and penthouse enclosures. Another important concern during the operation of the units was the consequences of an upset condition, i.e. high temperature or pressure. A bypass was incorporated into the design in response to the upset requirements.

The bypass required the tightness of a guillotine but the response of a louver. After a review of various dampers available, a double louver system was chosen. In order to maintain zero leakage a vent opening was placed in the center thereby allowing ambient air to leak into the bypass instead of particulate laden gases through the dampers.

In order to deter proposals from baghouse manfacturers who were inexperienced in the operation of utility boilers, proposals were accepted from qualified manufacturers only. A qualified supplier was one having at least one unit of a size capable of handling gases of a quantity equal to or greater than 100,000 ACFM on a utility boiler. As a result, bids were received from three manufacturers. The experience requirement and conservative specification notwithstanding, some skepticism still remained.

SELECTION OF TYPE OF EQUIPMENT AND VENDOR

As bids were received, a careful review was made of the qualified bidders and a separate evaluation was performed for the precipitators and baghouses. Items evaluated included pressure drop, power consumption, operating and maintenance cost, escalation, etc. As a result of the evaluation, Western Precipitation was evaluated low bidder on both the precipitator and baghouse. These two (2) particulate collection devices were again evaluated against each other with a resulting cost difference, based on a ten-year life, of $305,754 in favor of the fabric filter. The evaluation was based on a two-year life of the filter bags and maximum pressure loss through the baghouse. It is now evident with the number of baghouses in operation that these assumptions were quite conservative resulting in a greater cost difference between the two devices.

It was also recognized that the psychological advantages of very low opacity with a baghouse, irrespective of load, coal or operating procedures is difficult to assess monetarily and because of the experience with both hot and cold side precipitators at the Martin Drake Station, there was some doubt of the precipitator's ability to perform continuously in a satisfactory manner at the high collection efficiency required.

Therefore a difficult decision was made; purchase a pollution control device which did not have a significant amount of operating time but which promised to be the state of the art in particulate collection.

CHRONOLOGY OF BAGHOUSE INSTALLATION

An award was made to JOY Manufacturing Company, Western Precipitation Division on August 10, 1976 for the purchase of two (2) baghouses. The contract encompassed design, fabrication, erection and start-up of the baghouses. Milestones achieved during the performance of this work are shown below:

Purchase Order:	August, 1976
Completion of Engineering:	January, 1978
Commence Material Shipments:	March, 1978
Mobilization at Job Site:	February, 1978
Completion of Material Shipments:	June, 1978
Completion of Erection:	August, 1979
Initial Start-up:	March, 1980
Commercial Operation:	April, 1980

BAGHOUSE SELECTION CRITERIA

The baghouse system selected to filter flue gases emanating from the boiler is described as follows:

Total Flue Gas Flow Rate:	1,071,600 ACFM
Temperature:	295°F
Inlet Particulate Concentration:	5.25 gr/ACF
Maximum Sulfur Content:	1.5%
Guaranteed Outlet Particulate Concentration:	.0074 gr/ACF
Efficiency:	99.86%
Number of Baghouses:	2
Compartments Per Baghouse:	18
Filter Bags	
Quantity/Compartment:	156
Quantity/Baghouse:	2808
Material:	Fiberglass, Teflon coating
Size (Nominal):	12 in. X 31 ft. - 9 in.
Total Filter Area* (2 baghouses):	542,650 ft^2
Gross Air-to-Cloth Ratio:	1.97:1
Net Air-to-Cloth Ratio:	2.09:1
Net/Net Air-to-Cloth Ratio** :	2.22:1

* excluding cuffs and seams

** with four (4) compartments out for cleaning and maintenance

BAGHOUSE SEQUENCE OF OPERATION

The baghouse system supplied to the Utility was similar to that applied at the Sunbury Steam Electric Station of Pennsylvania Power and Light Company, i.e. fiberglass filter media with straight reverse air cleaning. Sunbury was the first electric utility to control steam generator emissions with a baghouse and had been in successful operation since February 1973. The reverse air cleaning concept can be broken down into four (4) distinct operations.

1. Filtering - Dirty flue gas enters compartment hoppers through the service damper. The gas flowing from the inside to the outside of the filter media is relieved of particulate. Clean gas then passes through the outlet dampers and exits the baghouse through the outlet plenum.

2. Settling - The first phase of the cleaning cycle begins as the gas outlet dampers in one compartment close. This establishes a "no-flow" or settle period in the compartment, allowing some of the captured particulate to descend into the hoppers for removal.

3. Reverse Air Cleaning - Gas flow is reversed through the bags when the reverse air damper is opened exposing the section to positive pressure from the clean side of the bags. Reverse air is provided by a fan which draws hot filtered gas from the baghouse outlet plenum. If necessary this reverse air period can be followed by another dust settling period and then another reverse air period before the section is returned to the filtering mode.

   To return the compartment to the normal filtering mode, the reverse air damper is closed and the gas outlet dampers opened. These two (2) outlet dampers are opened on a staggered basis and with very slow cylinder travel to reinflate the filter bags gently and avoid "popping" which can occur if the filtering elements are returned to full flow service instantaneously.

4. Isolation - By closing the reverse air damper, gas outlet dampers and service damper, the compartment can be completely isolated from the gas stream. When the upper and lower access doors are opened, fresh ambient air flows freely through the compartment. Personnel can then enter for inspection or maintenance.

BAGHOUSE DESIGN FEATURES

The design features deemed most important to the eventual successful operation of the baghouses are enumerated below. These items were either specified by the Architect/Engineer or offered as the manufacturer's standard design.

1. Low Inlet Velocity to Compartments - Flue gas is introduced into the compartments at velocities less than 15 fps. This allows fallout of larger dust particles prior to contact with the filtering elements, minimizes abrasion and reduces pressure losses.

2. Stepped Thimble Floor - In conjunction with the low velocity inlet the stepped thimble floor promotes even dust distribution across the compartment, which extends filter life.

3. 12" Long Thimbles - Thimbles of one bag diameter were supplied to minimize abrasion as the flue gas enters each bag. Thimbles are welded in place to ensure a 100% seal in the clean/dirty interface. Bags are attached to thimbles with no tools, reducing potential for damage during installation.

4. Ample Bag Spacing - 14" center-to-center spacing between bags ensures that adjacent bags will not touch, eliminating a common mode of bag failure.

5. Ratchet Tensioner - A "no-tool" stainless steel tensioner provided to allow quick, precise tensioning of filtering elements.

6. Enclosed Access - All devices requiring routine maintenance (pneumatic operators, high ash level detectors, etc.) are enclosed.

7. Fiberglass Filter Bags - Fiberglass filtering bags, 12" in diameter, 31'-9" long were provided. Bags supplied weighed 10 oz./yd.^{2} and included a 10% Teflon coating to resist the corrosive and abrasive potential in the flue gas. Seven (7) anti-collapse rings were provided along the length of the bag to ensure an open path for dust to flow during cleaning and to minimize fold lines in the fabric which can become points of failure.

START-UP OF THE BAGHOUSE SYSTEM

The boiler was initially fired on oil during December 1979 and January 1980 to complete the boiler boilout and steam blows. During this initial firing of the boiler, the baghouse was bypassed. While on bypass, the vent hatches for the compartments were opened slightly to allow outside air to enter the compartment and exit through the partially open outlet valve. This eliminated the possibility of any damaging flue gas entering the compartments and also protected against condensation.

It was found through experience that if the compartments were closed up tight, considerable condensation occurred.

On Monday, March 3, following completion of the baghouse checkout, baghouse "B" was first put in service. To approximate design air-to-cloth ratios, only a portion of the baghouse was put in service. The boiler was operated at approximately 35% load, 70-80 MW's, hence 10 of 36 total compartments were initially cut in. Since the fixed point in the baghouse structure is located in the center, the baghouse compartments were brought into service beginning with the center compartments and working toward the outboard compartments. This was done in an attempt to have the baghouse expand outward from the fixed points. By maintaining design air-to-cloth ratios, the individual compartments were heated more quickly and condensation/dewpoint concerns were minimized. As the temperature of these compartments stablized, the remaining compartments were added. Within 45 minutes, the entire "B" baghouse was in service. After the initial bleed through of particles, the filter cake formed on the bags and the opacity stabilized at 2.5% . On Tuesday, March 4, at 9:00 a.m. the "B" baghouse was cleaned for the first time. After one complete cleaning cycle, the differential pressure dropped to 0.9" water column.

On Tuesday, March 4, load was increased to approximately 65% and the "A" baghouse was put in service using the same procedure. Both baghouses were then cleaned on Thursday, March 6, when the differential pressure for "A" baghouse was 4.1" water column and the differential pressure for "B" baghouse was 5.2" water column. After cleaning unit "A", the differential pressure dropped to 0.7" water column and unit "B" dropped to 1.1" water column. The unit was at 120MW or 60% load at this point. The operating temperature of the unit ranged from 300 F to 330 F.

Once full load operation was attained, a continuous cleaning cycle was initiated.

The unit was declared commercial on April 1, 1980. Since that time the unit has been base loaded at 220 MW generally between 8:00 a.m. and midnight. From midnight to 8:00 a.m. the load is normally dropped to 50-80%.

PERFORMANCE OF THE BAGHOUSE SYSTEM

Particulate Emissions

Tests were conducted at both the inlet and outlet of the baghouse system since system efficiency, rather than an outlet emission, was guaranteed.

All particulate tests were performed according to E.P.A. Method 17 procedures as described in the February 23, 1978, Federal Register. This procedure uses a pitot tube alongside the filter holder or thimble holder to measure the gas velocity at the sampling points for the calculation of isokinetic sampling. The tests consisted of 240 minutes of sampling time with 48 test points per duct on the inlet and 10 minutes sampling time for 24 test points at the stack.

In order to conduct the tests at the design net air-to-cloth ratio of 2.09:1 a measurement of the gas volume was performed before each test to determine the number of compartments to remove from service. Two (2) compartments were removed from service per unit, before the first and third tests, and three (3) compartments per unit before the second test.

A summary of the particulate test results is contained in Table #1. All inlet test values contained in the table are composites of the "A" & "B" baghouse inlet test runs. Values expressed in dry standard cubic feet, DSCF, are based on 70°F and 29.92" Hg. Efficiencies were based on the measured inlet and outlet concentrations expressed in gr/DSCF. These measurements for the three (3) tests were respectively: 99.94%, 99.90%, and 99.93%.

Each test consisted of nearly simultaneous runs on the north and south inlet ducts and the stack. All tests were conducted during normal operation at full boiler production. No changes were made to the fabric filter cleaning schedule. Boiler soot blowing was conducted during the tests.

TABLE 1

Test Number	1	1	2	2	3	3
Location	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Temperature (°F)	295	302	299	302	302	303
Particulate Emission (gr/ACF)	1.80	0.0011	1.73	0.0017	2.02	0.0015
Particulate Emission (gr/DSCF)	3.39	0.002	3.28	0.0032	3.84	0.0028
Efficiency		99.94		99.90		99.93

Outlet emissions on similar installations have ranged from the above level to 0.01 gr/ACF.

Pressure Drop

The average pressure drop across the fabric filter during the tests was 3.5" water column. It ranged from 3.8" to 4.1" on the north or "A" unit and 3.1" to 3.2" on the south or "B" unit. The measured concentration of the north inlet was greater in all tests than the south inlet by 12. to 26%. The higher grain loading noted on the north unit influences the higher pressure drop noted.

Opacity

The opacity at the stack during the test program was approximately four (4) percent.

Stack opacity consistently ranges from 2-4% with no visible emissions.

Temperature Drop

With an average inlet temperature of 300-325°F temperature drop across the baghouse system is 10-12°F.

Filter Bag Failures

Since the initial start-up, it has been necessary to replace a total of seven (7) bags. These were all due to cuts, etc. and can be attributed to the installation.

OPERATIONAL AND MAINTENANCE PROBLEMS

1. One of the most time consuming problems with the baghouse is the maintenance and operation of the key interlock system. The Nixon baghouse has 36 compartments: each compartment has two (2) upper doors and two (2) lower doors plus one door on the hopper totaling 180 doors. Each compartment has four (4)

dampers (1-inlet, 1-reverse air, 2-outlet) totaling 144. The doors and door locks on the baghouse are of the highest quality obtainable. Because the locks on these systems are not used regularly and because of the extreme heating and cooling and exposure to moisture and fly ash, the locks and linkages tend to bind up. During a unit outage, when it is necessary to open all doors for inspection, opening and closing of the baghouse doors becomes a major project. We have found that it takes two (2) men 16 hours to open or close all doors. To date, we have broken seven (7) keys on the interlock system due to jamming. The interlock system on the baghouse is a carryover from the electrostatic precipitator and it is felt that there is only limited need for such a system on a baghouse. Rather, it would be sufficient to simply provide a means of padlocking dampers in the safe position for maintenance while on line. It should be noted that maintenance of the baghouse while on line is less dangerous than maintenance on other power plant equipment, such as pulverizers, breakers, large motors, fans, etc., and that the real protection is adherence to a good tagging and clearance procedure. The Owner's recommendation on future units would be to delete the key interlock system.

2. An additional maintenance problem that has been experienced on the unit is the expansion joints in the reverse air system. The design of the expansion joints was inadequate resulting in the failure of said joints after approximately four weeks of operation. This did not present an operational problem in that cleaning the bags was possible even with the expansion joints completely missing on three sides. These expansion joints were replaced by Western Precipitation and again failed after approximately four weeks of operation. A third generation of expansion joints, specially designed and manufactured by Western Precipitation, has replaced the purchased joints previously supplied. These joints include revised mounting flanges which have resolved the problem.

CONCLUSIONS

The success of the R.D. Nixon installation, i.e. low outlet emissions, low pressure drop and zero visible emissions stems from a number of factors:

1) Conservative air-to-cloth ratio - 2.09:1 net.

2) Large number of compartments with comparatively few bags per compartment (156). This minimizes large-scale swings in a ΔP during cleaning and maintenance operations.

3) Sound engineering procedures regarding start-up, i.e. no precoat and bypass during oil light-off.

4) Vigilant maintenance procedures.

POTENTIAL FOR IMPROVEMENT IN BAGHOUSE DESIGN

By: Robert M. Jensen, Bechtel Power Corporation, San Francisco, CA

ABSTRACT

This paper describes the potential for improvement in design of large, structural, reverse air baghouses of the type now being applied to remove fly ash from large coal-fired power plants. It is intended to demonstrate that some currently acceptable and recommended design details cause unnecessary pressure loss, increase the energy required for cleaning, and decrease bag life. In addition, the discussion indicates that these improvements are more significant for the utility industry than for industrial users because of differences in evaluation methods.

INTRODUCTION

The baghouse designs under consideration are limited to "large structural" or "large custom design" baghouses, especially those now being used to remove fly ash from the flue gas of large coal-fired power plants. Shaker-cleaned and pulse-jet baghouses are not considered. The design elements in need of improvement are as follows.

Hopper Fallout

In technical literature, commercial brochures, and advertisements, hopper fallout is described as a desirable feature. It is claimed that hopper fallout reduces the amount of material to be collected by the bags, thus reducing cleaning frequency and resulting in less cleaning energy and longer bag life. These claims may not be justified; in fact, the opposite may be true.

The generally accepted expression for fabric filtration pressure loss across the cloth and filter cake is:

$$\Delta P = k_2' \times C_i/7000 \times t \times V^n$$

Where:
ΔP = pressure loss in inches of water column
k_2' = a constant, in. wg ÷ $(\text{lb/ft}^2)(\text{ft/min})$
C_i = inlet grain loading, grains/actual cu ft (ACF)
t = time in minutes between cleanings
V = cloth ratio in ft/min
n = a number between 1 and 2.

In using this expression for pressure loss, it is customary to use the value of k_2' for the median particle size in the filter cake even though it varies with particle density, particle size, gas viscosity, and gas temperature. For a given application we can assume that particle density, gas viscosity, and gas temperature are constants.

Particle size distribution in filter cake and hopper fallout has been reported by Robinson et al (1) and is reproduced in this paper as Figure 1. The variation of k_2' with particle size has been reported by Noll, et al (2) and is reproduced in this paper as Figure 2. The median size of particles in the cake, taken from Figure 1, is shown on Figure 2. The median size of particles in the inlet gas stream, assuming 15% wt fallout, is calculated from Figure 1 and shown on Figure 2.

With no hopper fallout k_2' would be about 9.5, as opposed to 13 with 15% wt fallout. Applying this reduction as a percentage to a typical cloth and cake differential of 4 in. wg would reduce the differential by approximately 1 in. wg.

We can hypothesize that the representative value of k_2' without hopper fallout is less than with fallout due to the change in composition of the filter cake. With hopper fallout the particles in the cake are small and are all in a narrow size range. Small particles pack into a low-porosity, dense cake. Without hopper fallout the particles in the cake have a larger median size and a wide range of particle sizes. Filter cake with a wide range of particle sizes is more porous and has a lower pressure loss than a cake entirely of small particles. It also requires less cleaning energy.

If we can design an improvement to eliminate hopper fallout we can reduce pressure loss, increase bag life, and reduce both the frequency of and the energy required for cleaning.

Redeposition

As dirty gas rises in a bottom inlet bag its vertical velocity diminishes. In a 12-in. diameter, 30-ft long bag at a cloth ratio of 2 fpm, the entering velocity will be about 240 fpm. Near the top of the bag the velocity will approach zero. This velocity reduction limits the ability of the gas to carry particles upward in the bag. As a consequence, the bottom inlet bag serves as a sort of classifier, with the fine fraction of particles accumulating in the top of the bag.

During reverse air cleaning some of the fines at the top of the bag will have agglomerated and will fall out; some will adhere to the cloth; and some will float in the top of the bag and again return to it as soon as the bag comes back on line. The latter is called redeposition.

If we take a solid sphere of fly ash, 1/2 micron in diameter, 80 lb/cu ft specific density, and use Stokes' Law to calculate its terminal velocity in still air, the particle will reach its terminal velocity in less than a second. At that velocity the time to travel 30 ft from the top of the bag to the hopper is approximately 1 year. In reality a single small particle will never make the trip alone because its fall will be opposed by the stack effect, or natural draft, in the bag.

We can assume that after a bag has been in service for a period of time, a certain portion of the fines in the top of the bag will be dislodged and returned to the bag every cleaning cycle. Obviously, this is not a cumulative process because the bags do not plug solid. Therefore, it is likely that some combination of conditions at the top of the bag releases some agglomerated fines during cleaning.

A typical pressure loss versus time plot for a single bag or compartment is shown as curve A on Figure 3. In our formula for ΔP we can assume that $k_2' = 50$, $C_1 = 3$, $n = 2$, and using values for ΔP and t for points on curve A of Figure 3, we can solve for V, the cloth ratio. A plot of V obtained in this way, versus time, is shown on Figure 4. Note that for curve A cloth ratio decreases with time. We can assume that the cloth ratio of a bottom inlet bag is variable and approaches zero near the top where redeposited fines form an impermeable cake. This cake blinds the top of the bag and, in effect, reduces its cloth area. Thus redeposition results in increased pressure loss and filtering capacity of a conventional baghouse compartment during each cleaning cycle. The reduction must be compensated by an actual cloth ratio for the baghouse that is higher than its design cloth ratio.

A well-documented characteristic of conventional baghouses is the gradual increase of pressure loss in new bags with time in service. It is the author's opinion that this is caused by a decrease in filtering capability at the top of the bag with steady usage over an extended time period. This gradual increase in pressure loss probably occurs at a faster rate as bag length increases.

If we assume that 10% of the bag goes blind at the top there will be an increase of 10% in cloth ratio which will increase pressure loss by approximately 0.6 in. wg.

Spring Tension

The notion that there is a single correct tension for each application of bottom inlet bags is not consistent with the actual necessity to re-tension after the bags have been in service for a period of time. It is also inconsistent with a type of bag damage caused by inadequate tension.

A typical spring might have a spring constant of 40 lb/in. A 12-in. diameter, 30-ft long bag might be installed with 40 lb of tension by compressing the spring 1 in. If we assume that a new bag weighs 10 lb (not including the chain nor the cap, but including the anti-collapse rings), we find that tension in the warp fibers at the top of the bag is 40 lb while tension at the bottom of the bag is 30 lb. If, during a cleaning cycle, the bag accumulates 30 lb of particulate, the tension at the top of the bag is 70 lb while there is zero tension at the bottom.

The so-called correct tension is one that does not make the bag so taut that it will not clean, nor so slack that the bottom of the bag will droop over the top of the thimble. The initial tension may satisfy these two requirements at certain times, but it cannot always be adequate because the bag's weight changes during each cleaning cycle. Moreover, the tension is always greatest at the top of the bag and least at the bottom. During reverse air cleaning the air flow (clean gas flow) is from outside to inside. Cleaning is accomplished by: a change in cloth shape, which releases the cake; reverse flow through the cloth, which also helps to release the cake; and downflow in the bag, which assists gravity in moving the released particulate to the hopper.

Anti-collapse rings, spaced along the length of the bag, are used to limit shape change. The warp fibers change from straight to a catenary shape between the rings. In cross section the fill fibers change from a circular shape to a multi-lobed ring with the least diameter midway between the rings. If tension is too great these shape changes may not be adequate to break the cake loose. If tension is too little the rounded, fluted lobes may collapse into vertical creases and the diameter between rings may be so small that the fall of the particulate will be impeded resulting in bag abrasion. Because of this variation in bag tension, there is more need for anti-collapse rings at the bottom of the bag, where tension is reduced, than at the top where tension is greatest. Variable tension and the irregular spacing of anti-collapse rings in the bag cause unequal shape change during cleaning. As a result, cleaning effectiveness is not uniform over the length of the bag.

We can assume that cleaning efficiency is greatest at the bottom of the bag where there is a high concentration of friable filter cake and a maximum change in bag shape. The initial reverse flow cleans the bottom of the bag which then becomes the path of least resistance for the balance of the reverse flow. The top of the bag has the highest tension, the greatest amount of cake, and a cake composition that is more difficult to remove. Thus we have the most difficult cleaning to do at the top of the bag where we have the poorest cleaning efficiency.

Another undesirable aspect of spring tension is bag stretch which makes it necessary to re-tension the bags from time to time. With inadequate tension the bottom of the bag hangs down on the outside of the thimble and forms a pocket which collects particulate. Motion of the bag causes the cloth to rub against the particulate resulting in abrasion in this part of the bag. When the bag goes into the cleaning mode, the excess cloth at the bottom is blown to the inside of the thimble where it hangs down in folds. Material falling down the bag hits one side of these folds, thus causing a second kind of abrasion on the same part of the bag. When the bag is put back on line it is blown to its position hanging down outside the thimble. The incoming flow of dirty gas strikes the other side of the folds, causing a third kind of abrasion on the same cloth. This scenario, illustrated by Figure 5, explains why the bottom of this type of bag is prone to pinholing, a very common type of damage leading to bag failure.

A popular explanation maintains that pinholing is caused by high inlet gas velocities as the gas enters the bottom of the bag. One remedy, assuming that the cause is high velocity, is to make the thimbles at least one bag diameter in length. The vena contracta caused by the entrance will then expire within the thimble and the flow leaving will be in streamlines parallel to the cloth. However, although long thimbles may be beneficial they cannot correct the damage caused by loose, extra cloth at the bottom of the bag. In addition, there is some evidence that gas velocity, in the range of 200 to 300 fpm, is not the cause of pinholing.

Pinholing at the bottom of the bag may be aggravated by null periods. Null periods are short intervals during a cleaning cycle when there is no pressure differential across the bags. They are favored by some suppliers who insist that they provide an opportunity for the particulate to settle out. This theory should be questioned for several reasons. During a null period the only force available to cause particles to settle is gravity, which is not adequate to overcome the buoyancy of gas in the compartment when there is a thermal gradient from the bottom to the top. If there is any slack at the bottom of the bag, the slack will hang down inside the bag, as shown by Figure 5, but it will move down at the beginning of the null period and up at the end of the null period. This movement aggravates wear on this portion of the bag. Null periods also lengthen the cleaning cycle, increasing the length of time that cloth area is out of service, and prolonging the pressure loss increase when a compartment is off line for cleaning. Finally, null periods increase the number of times a bag will be flexed, which diminishes bag life. In sum, null periods do not help the cleaning process, but rather add to pressure loss, increase cleaning energy, and diminish bag life.

In conclusion, spring tension is detrimental to bag life and may be the cause for particle penetration. It also contributes to uneven cleaning and increased cleaning energy.

Recirculation

The clean reverse flow entering the compartment during reverse air cleaning becomes a dirty flow leaving the hopper and entering the inlet duct. This dirty flow has to be cleaned by the on-line compartments. It is a flow that has already been cleaned and whose particulate has been previously collected in other compartments. This process of returning the reverse flow and some particulate to the inlet duct is called recirculation.

The amount of the reverse flow is determined by design and included in the so-called net cloth ratio. The amount of particulate in the reverse flow is indeterminate. Recirculation undoubtedly entails pressure loss; costs an increment of bag life; and uses an excessive amount of cleaning energy. If recirculation increases the grain loading at the inlet to the bags by 10%, the increase in the pressure loss will be approximately 0.4 in. wg.

Ventilation

Before workmen may enter a compartment for inspection or maintenance work the compartment must be purged of gas, cooled to a tolerable temperature, and ventilated by fresh air. This is usually done by closing the outlet, reverse air, and inlet dampers so that access doors can be opened. After the access doors have been opened the inlet damper can be partially opened so that outside air will be sucked in to purge, cool, and ventilate the compartment. In addition, this arrangement prevents the escape of fugitive dust from the compartment.

Without a separate ventilation system, the outside air drawn through the compartment enters the inlet duct. Air temperature is lower than gas temperature and air may have a significant moisture content. The ventilation flow thus cools the gas and may increase its moisture content. This can be detrimental to the bags and the house if the system is operating near the acid dew point. Ventilation flow occurs at a time when the cloth area of the baghouse has been reduced by taking a compartment off line and is added to the normal flow, thus causing an increase in cloth ratio and pressure loss. These disadvantages are diminished if the baghouse is equipped with a separate ventilation system.

A compartment may be off line for several hours before it is safe and cool enough for workmen to enter. Work in the compartment may be a matter of minutes or hours. In any case, baghouse pressure loss is increased for the duration of the outage.

Some filter cakes are hygroscopic and will pick up water from the air during a compartment outage. The resultant wet cake, which may be somewhat pozzolithic, may set into a hard cake, or glaze, when the bags come back on line. During subsequent cleaning cycles some of this hard cake will fall off and some will not. The hard cake that remains will be in patches with sharp, jagged edges. Bag shape changes will be resisted by the remaining hard patches of cake, and fibers will be damaged by the jagged edges.

This ventilation procedure also makes it necessary to subject the bags and the interior of the compartment to two excursions through the acid dew point: once on the way down and once on the way up in temperature. During such excursions through the dew point, the cloth, the thread used in making the bag, and the finish on the cloth suffer some damage. Damage varies in relation to the amount of sulfur trioxide present in the cake on the bags. These excursions will also result in corrosion of bag hardware, access door gaskets, and the house.

Ventilation is, thus, a cause of pressure loss and a detriment to bag life. These shortcomings can be alleviated by reducing the time required to prepare for entry after the access doors are opened; and by reducing the time required to clean the tubesheet, remove defective bags, and install new bags. With or without a separate ventilation system, a better procedure for gaining access to a compartment is one of the most needed design improvements.

Re-entrainment

Some dust collector users store the collected material in the collector hoppers for many hours, typically one or two shifts of 8 hours. With a baghouse, this length of storage will span a number of cleaning cycles. As an extreme example, a baghouse cleaning cycle might cover every compartment twice an hour and the storage might be for two shifts. In this case material collected during 32 compartment cleanings would be stored in the hoppers.

Depending on the inlet grain loading and the hopper size and shape, the level of material in the hopper may be near the bottom of the inlet duct. This would be likely in the aforementioned extreme case. If the level of stored material is high, or if the inlet is baffled in a way that turns the incoming gas flow downward, material may be swept off the surface of the collected material and redeposited on the bags. This process is called re-entrainment. One safeguard against re-entrainment requires emptying the hoppers before the level of stored material gets too high. If re-entrainment occurs, it leads to recollecting and recleaning which once again wastes time and energy; increases pressure loss; and decreases bag life.

If re-entrainment were to increase the grain loading at the inlet to the bags by 5%, the pressure loss would increase about 0.2 in. wg.

Rehandling

In this description of potential design improvements, it has been noted that some of the particulate is collected, removed from the cloth, redeposited, recirculated, and re-entrained. We might call these processes rehandling.

In Figure 6 the numbered circles are as follows:

1 - The grain loading in the gas leaving the process; i.e., leaving the air preheaters of a coal-fired power plant.
2 - Hopper fallout.
3 - Material collected in the bags and transferred to the hopper during a cleaning cycle.
4 - The fine particle sizes at the top of the bag which adhere to the bag or move off of the bag at the start of cleaning and back on the bags at the end of cleaning, i.e. redeposition.
5 - Particulate in the reverse flow returned to the inlet duct during reverse air cleaning, i.e., recirculation.
6 - The actual inlet grain loading to each compartment. The sum of No. 1 and No. 5.
7 - Material picked up from the surface of material stored in the hopper and redeposited on the bags, i.e., re-entrainment.

This schematic diagram illustrates the number of ways and suggests the number of times that particulate is handled and rehandled.

It takes energy to move particulate around and to move gas through a filter cake. If particulate in the cake is collected repeatedly, there is unnecessary energy loss that could be avoided through elimination of redeposition, recirculation, and re-entrainment. Rehandling also entails greater cleaning frequency, and greater bag abrasion, both of which reduce bag life. The ideal baghouse design would provide for the handling of a particle only once: collect it once and transfer it from the bag to the hopper once.

Redeposition at about 0.6 in. wg, plus recirculation at 0.4 in. wg, added to re-entrainment at 0.2 in. wg, together with a hopper fallout pressure loss of about 1 in. wg give a total of 2.2 in. wg, which a utility would evaluate at approximately $2,000,000 for a 500-MW plant (3).

Conclusion

Design improvements are needed to reduce operating costs, which are of greater concern for utility applications than for most industrial applications. Industrial users want a fast payback; they do not evaluate baghouse use for a 35 to 40 year equipment life. Operating cost can be recovered in the selling price of their product which is not price-regulated by a public commission. As long as all baghouses remain so similar in design and operating cost, the industrial user has little incentive to reduce operating cost because his competition is buying the same kind of baghouse with the same capital and operating costs. He is especially not interested in saving operating cost if he must pay a higher capital cost.

Utilities, on the other hand, can add capital cost to their rate base and may qualify for tax credit for purchasing pollution control equipment. Utilities are very concerned with operating costs because they affect the selling price of electricity which is regulated by a public commission and because they have to be evaluated for a 35 to 40 year plant life.

When the market for coal-fired power plant baghouses started to develop in the early 1970s, the expedient method of supply was with the conventional baghouse designs that had been developed for the industrial market. Now, in the early 1980s, at a time when there is great emphasis on conserving energy and reducing production costs, we are still using the industrial baghouse design for both industrial and utility applications.

In this paper the author has attempted to identify some potential design improvements. Although individual improvements may contribute only a small saving of pressure loss, it is possible that the total pressure loss that could be saved would be significant. Similarly, although individual design details may contribute only a small amount of bag damage, it is possible that improving a number of them would result in significantly longer bag life. In addition, the individual corrections may be synergistic; correcting one deficiency may make it possible to correct another. It is the author's hope that this paper will stimulate the development of design improvements.

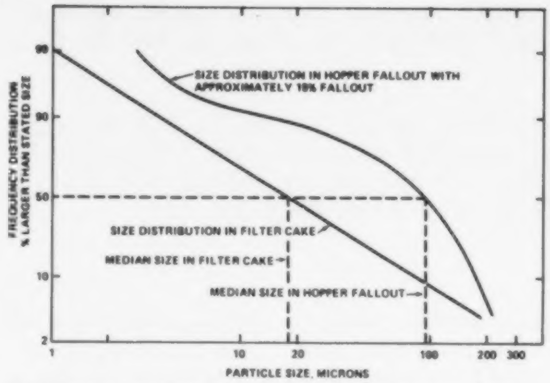


FIGURE 1 PARTICLE SIZE DISTRIBUTION OF FLY ASH IN FILTER CAKE AND HOPPER FALLOUT

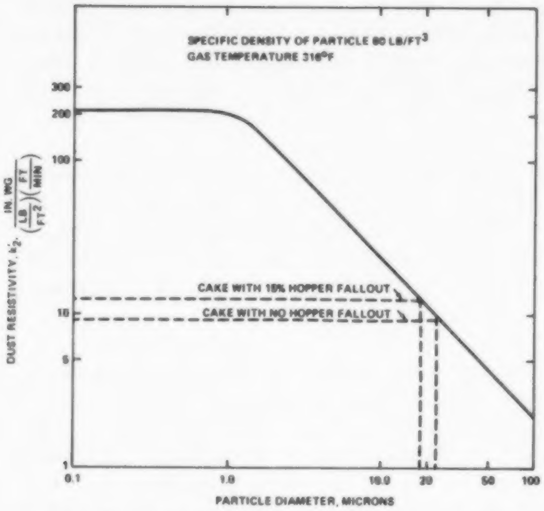


FIGURE 2 VARIATION OF k_2' WITH PARTICLE SIZE

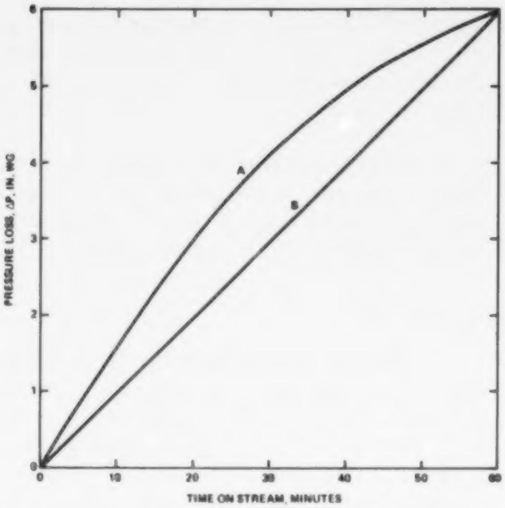


FIGURE 3 PRESSURE LOSS VERSUS TIME DURING ONE CLEANING CYCLE

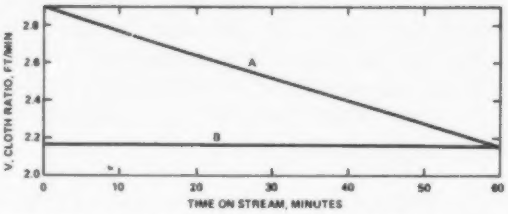


FIGURE 4 CLOTH RATIO VERSUS TIME DURING ONE CLEANING CYCLE

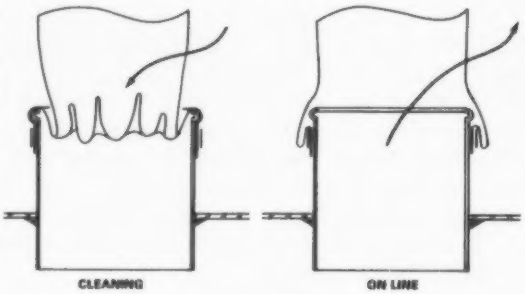


FIGURE 5 BAG BEHAVIOR AT THIMBLE WITH INADEQUATE TENSION

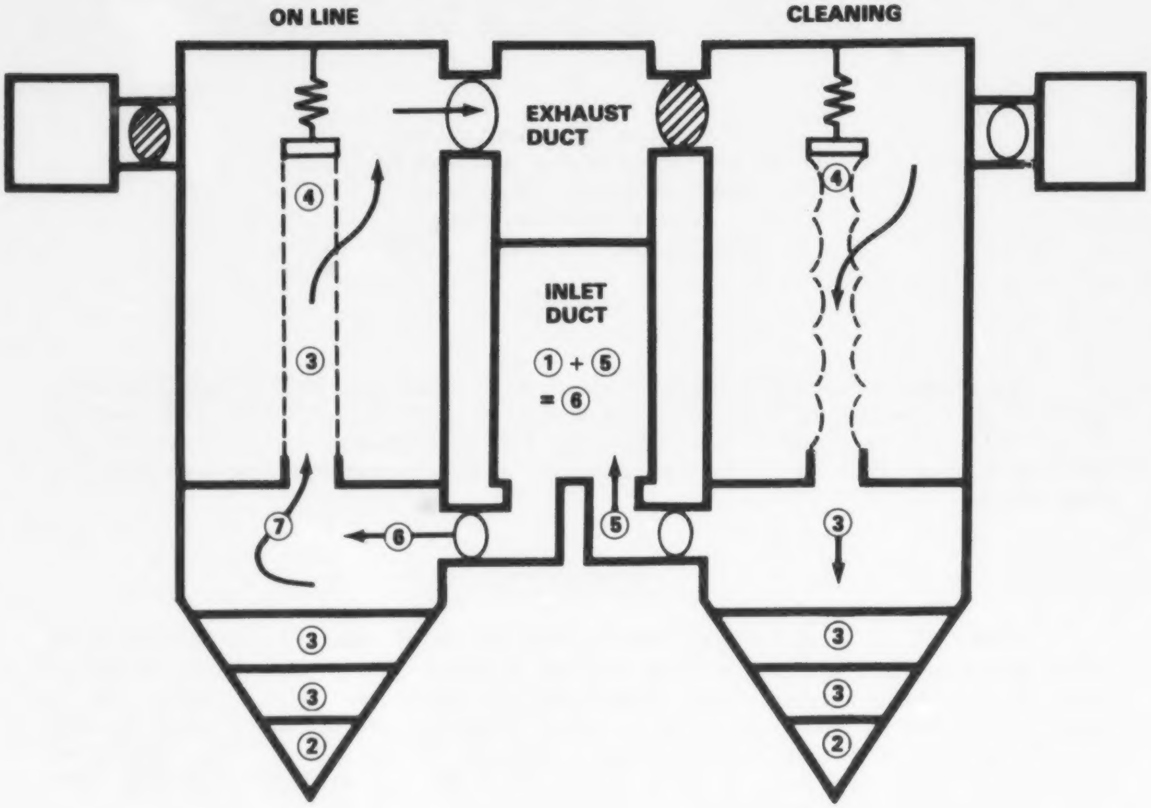

ON LINE
CLEANING
EXHAUST DUCT
INLET DUCT
① + ⑤ = ⑥
④
③
⑦
⑥
⑤
③
③
②
④
③
③
③
②

FIGURE 6 PARTICULATE RE-HANDLING

ENDNOTES

1. Robinson, J.W., R.E. Harrington, and P.W. Spaite, A New Method of Analysis for Multicompartmented Fabric Filtration. Atmos. Environment 1, 495 (1967).

2. Noll, K.E., W.T. Davis, and S.P. Shelton, New Criteria for the Selection of Fabric Filters for Industrial Application. (Paper 73-301 presented at A.P.C.A. Annual Meeting 1973).

3. Jensen, R.M., Baghouse Bid Evaluation. (Presented at 2nd International Fabric Alternatives Forum, 1977).

REVIEW OF OPERATING AND MAINTENANCE EXPERIENCES WITH HIGH TEMPERATURE FILTER MEDIA ON COAL-FIRED BOILERS

By
L. K. Crippen, Ph.D.
Marketing Representative
E. I. du Pont de Nemours and Company, Inc.
Textile Fibers Department
Centre Road Building
Wilmington, Delaware 19898

ABSTRACT

Experiences on full-scale coal-fired industrial boiler applications using high velocity outside collectors fitted with Teflon® TFE-fluorocarbon fiber felts is reviewed. Key operating and maintenance concerns which can influence bag life and performance at high operating temperatures is summarized.

INTRODUCTION

Today, I will narrow my presentation to cover some of our experiences with particulate control on coal-fired boilers which use high velocity outside collectors with high temperature filter media. I will use a number of case studies to give a brief description of a variety of our actual operating and maintenance experiences. In addition, key operating and maintenance concerns as well as factors which can influence bag life and performance are summarized.

Fisher Body's Side Stream Separator

Fisher Body, a division of General Motors Corporation, employs a Western Precipitation pulse-jet baghouse to collect the fly ash exhausted from the hopper of a multicyclone which acts as the primary collector (1). Western Precipitation originally used a multicyclone instead of a baghouse behind the initial multicyclone. Optimization of the primary multicyclone led to collection efficiencies in the range of 94% - 96%, and outlet particulate concentrations in the range of 0.30 - 0.35 lb/MM Btu with no hopper exhaust gas flow. When 15% - 20% of the flue gas was exhausted through the hopper to the baghouse, the stack emission was reduced 50% resulting in emissions of 0.12 - 0.16 lb/MM Btu.

This improvement far exceeded what one would expect from simply filtering 15% - 20% of the flue gas. That would reduce the emission to 0.255 - 0.298 lb/MM Btu, so the hopper exhaust apparently does improve the flow pattern in the primary cyclone and increase its efficiency.

Fisher Body has installed eleven of these systems in their retrofit program on spreader-stoker boilers. Ten of the operating units have bags of felted Teflon® fiber and one had bags of glass felt. The Fisher Body design project engineers reported typical Δ P for Teflon® TFE-fluorocarbon fiber felt from 4-6" and glass felt at 5-7". The first full-scale unit was installed at the Hamilton, Ohio plant of Fisher Body in September, 1978, on a 52,000 lb/hr boiler. None of these installations have had a single Teflon® bag failure. However, the glass felt has just recently failed presumably due to the frequent dew point excursions associated with their week-end energy saving shut downs.

Du Pont Plant Update

The Du Pont Company operates a plant in West Virginia where the spreader-stoker boilers are equipped with a combination of multicyclone collectors and baghouses. Boilers 2, 4, 5, and 6 have single stage mechanicals preceding the baghouse. This installation was the first coal-fired powerhouse equipped with pulse-jet baghouses with bags of Teflon® felt, and several papers (2, 3, 4, 5) have been written about the design and early performance of the equipment. Today, I will present an update on this operation.

Operating Temperature

The baghouses run in a temperature range of 330°F (166°C) to 400°F (204°C). Below 300°F (149°C) there is danger of sulfuric acid corrosion to the baghouse. The coal contains about 2.6% sulfur which does not damage the bags, but it does corrode the baghouse casing.

Bag Replacement

The baghouses have been in operation nearly six years now, and many of the original bags are still in service. Table I shows the annual bag replacement since start-up. So, at the end of 1980, after five years, 63% of the bags have been replaced, approximately 59% due to wear. However, after the first three years, no bag failures had occurred due to wear; in the fourth year, only 1% were replaced due to wear.

The failure rate is plotted in Figure 1 (see back). The dashed line shows the annual failures from Table I and the solid line shows cumulative failures, with linear extrapolation past 1980. This line intersects the "complete set" ordinate at about March of 1982, so we predict complete failure of the original set of bags at that time. The annual failure rate follows a bell-shaped curve, in which the average bag has a life of 5.3 years, and the oldest bag is expected to fail after 6.5 years.

The bags are replaced when the stack opacity increases. Transmissometers located in the baghouse exit breeching tell the operator that fly ash is escaping. The operator then switches compartments off line until he finds the compartment which when valved out, makes the stack clear up. That is the compartment with the leaking bags. The boiler is shut down and a fluorescent powder is fed into the baghouse inlet breeching (6). This powder, Visolite, is sensitive to black light which makes it fluoresce. The compartment is again valved out of service and tagged, locked, cleared, and tried. Then the operator enters the penthouse, opens the access doors, turns off the lights in the penthouse, and scans the venturis with black ultraviolet light. The venturis that fluoresce are marked for bag replacement.

The maintenance crew removes the marked bags, vacuums and inspects them. A bag which has only one hole, perhaps because of a broken cage wire, or possibly a stitching failure in the bottom disk, is sent off to a repair shop. Bags which show general wear are discarded. New bags are installed as needed, but so far the plant has not found it necessary to replace all of the bags in one compartment at the same time.

TABLE I

DU PONT WEST VIRGINIA PLANT BAG FAILURES

Year	Bag Failures	Remarks
1975	99	54 burned in hopper fire, 45 bottoms ripped out.
1976	39	17 burned by weld spatter, 22 bottoms ripped out.
1977	25	2 came unclamped, 23 bottoms ripped out.
1978	40	Wear
1979	1069	Wear
1980	1252	Wear

End 1980 total replaced = 2,524
Complete Set of Bags = 4,018

Tennessee Plant

Du Pont operates a plant in Tennessee, which has four 145,000 lb/hr boilers burning 3% sulfur coal. Boilers 1 and 2 are spreader-stokers, and 3 and 4 are chain-grate stokers. Boilers 1 and 4 are equipped with 2-stage multicyclones, and boilers 2 and 3 have pulse-jet baghouses similar to boiler 5 at the West Virginia plant. Bag life has been similar to that at the West Virginia plant.

Staclean™ Diffusers

A. S. Johnson, Jr., Partner of Carolina Stalite Company of Salisbury, North Carolina visited the Tennessee Plant in December, 1978 and learned that the Teflon® TFE-fluorocarbon fiber bags operated successfully. However, he noticed some wear had occured on the inside of some of the bags after three years. The wear was fairly uniformly distributed around the inner surface of the bag and limited to the top three or four feet of the bag and was attributed to fly ash erosion.

A. S. Johnson thought about the wear and invented a solution to it. He sketched a perforated tube which could be placed inside the cage, to shield the bag from the erosion flow of fly ash (7). His idea developed into a product known as a Staclean™ diffuser which has been patented in the U.S. and has foreign patents pending. The manufacturer claims that in addition to reducing wear, use of the diffusers results in improved bag cleaning and reduced pressure drops.

In the summer of 1980, the Tennessee plant installed a complete set of Staclean™ diffusers in the two baghouses serving Boiler 3. The baghouse pressure drop was reduced from 10" water to the range of 5" to 6" water, and that level has been maintained for several months.

Calculated Savings

It is a bit early to say how much bag life has been extended, but after discussion with plant personnel, the following calculated savings justify the installation of Staclean™ diffusers on Boiler 5 at the Du Pont plant in West Virginia (Table II).

Cost for the 1,176 Staclean™ diffusers is $35 each, plus $25 each for transportation and installation; $60 per diffuser for a total of $71,000. Investor's method return for the installation is 59%. The entire calculations are too lengthy to present here.

The West Virginia Plant has purchased diffusers for the #5 boiler baghouses, and performance data are expected shortly. The Staclean™ diffusers will be installed in dirty bags to give a direct measure of pressure drop savings attributable to the diffusers.

TABLE II

CALCULATED COST SAVINGS WITH DIFFUSERS*

Horsepower	$15,000/yr
Compressed Air	8,000/yr
Bag Replacement	9,000/yr
Bag Washing	3,000/yr
TOTAL SAVINGS	$35,000/yr

* Tennessee Plant

ETS Monitored Baghouse

An Enviro-Systems baghouse on a stoker-boiler has been monitored by ETS, Inc. through a contract from the Environmental Protection Agency. Six hundred and forty-eight bags of Teflon® TFE-fluorocarbon fiber have been in service for a total of three and one half years. After 27 months at the first site, a fire occured in the main plant; however, the boiler, baghouse, and bags were not damaged. The boiler and baghouse were moved to a new site. The Teflon® bags were boxed and shipped to the new site where they were reinstalled and have been in service now for an additional 15 months.

The Enviro-System's baghouse at the original installation used reverse air flow for cleaning. However, pulse assist using approximately 90 psi was added. The baghouse currently operates between 400°F - 450°F (204°C - 232°C) (Table III). The operating and maintenance procedures used at this site have been well developed over the years to react to a variety of potential problems (8).

The baghouse operates 5 to 5-1/2 days a week and has gone through many shut-downs and total cold re-starts. Eventually, off-line cleaning is used to remove the cake which built up during cycling through dew point. Nodules also developed and became attached to the bags at the original site. Eventually, the bags would have to be cleaned in place using a combination of vacuum suctioning and scraping. This procedure has not been necessary since the addition of pulse assisted cleaning.

Despite the severe chemical and physical environment, the bag failure rate was approximately 5%/yr for the first 27 months and approximately 5.7%/yr for the last 15 months.

TABLE III
FLUE GAS PARAMETERS*

Type	1st Site	2nd Site
Gas Flow (ACFM):	30,000-34,000	35,000-38,000
Gas Temperature:	300°F (149°C)	400°F - 450°F (204°C - 232°C)
Inlet Loading: (gr/DSCF)	0.5 typical	0.2 - 0.5 typical
Bag Failures:	5%/yr	5.7%/yr
Operating Cycle:	5 - 5-1/2 days/wk	5 - 5-1/2 days/wk

* ETS monitored baghouse.

Routine Operating and Maintenance Considerations

We have learned a lot from our field experiences in relation to routine operating and maintenance procedures and bag use. Much has been written about general operating and maintenance practices and procedures (6, 9, 10). However, we are all still learning about the use of filter media in this application. I would like to summarize some general points which I have found to be key from my field experiences.

Get to know your entire system.

System variables you need to become very familiar with include the design and operation of the boiler including start-up and shut-down procedures; baghouse design including the cleaning mechanism, fly ash storage and removal; monitoring instrumentation; filter media; the type of coal, fly ash characteristics, and gas stream chemistry.

Experiment with the operation of the system.

Experimentation is essential to developing a good working relationship with your baghouse.

Keep excellent records.

Record keeping can offer valuable assistance in solving the simple to the complex problems. Keep accurate records of bag replacement and a diagram showing replacement patterns for your entire baghouse. This record should include the date of the bag change, the type of bag installed, the location, detailed description of the failure, and an evaluation of what contributed to the bag failure.

Develop a step-by-step problem solving approach.

Develop a step-by-step problem solving plan based on operation of your system. The plan should be practiced and modified when necessary. Quick action is often necessary when a problem is encountered; hence, the need for a plan.

Obtain assistance when needed.

Unusual operating conditions should be noted immediately and determination made as to possible causes. Be sure to examine the entire system. Get people involved who understand all segments of the operation including the various types of filter media. However, you should start with your original equipment manufacturer.

Filter Media Considerations

From our field experience, I have compiled a checklist (Table IV).

TABLE IV
FILTER MEDIA CHECKLIST

Concern	Check
Bag Installation	Recheck bag seating/reduce bag change outs
Bag Construction	Reinspect bags before installation
Chemical Degradation	Choose chemical resistant media and thread
Mechanical Failure	Periodic bag evaluation to predict bag life
Bag Cleaning	Experiment with cleaning mode and timing; check pulse action; evaluate air flow
Bag Sizing/Fit	Follow recommendation for specific filter media; Teflon® TFE-fluorocarbon fiber oversized to recommendation
Cake Release	Try off-line cleaning; refurbish bags, e.g. vacuum/wash
Embers in Baghouses	Cyclones before baghouse/pull ash

Bag Sizing

Our experiences in the field and laboratory indicate the need for correct bag sizing with Teflon® TFE-fluorocarbon fiber bags. Your felt supplier, either Du Pont Fabric and Finishes Department or Albany International, should recommend the percent of oversizing for your specific operating conditions based on their expected shrinkage at your operating temperature. This oversizing allows the bag to inflate properly when pulsed thus allowing the cake to blow off. Teflon® fiber bags which are sized too small may eventually shrink tight on the cages which can lead to poor bag cleaning.

Due to the pliable nature of this felt, problems with flex failures have not been observed. Stiff fabrics when oversized can wrinkle and fail due to flexure; hence, their sizing requirements differ. Due to the range of performance for fibers and filter media, you should use recommendations for your specific filter media.

Washing a correctly sized bag should present no problems when done properly. This can be a big advantage to your operating and maintenance cost since a process upset or problem does not mean that you have to throw all the bags away. The bags should be sent to a cleaner who has had previous experience in refurbishing bags. It is also possible to repair bags where small holes have occurred. In many cases, the organization refurbishing your bags will determine whether the bag is worth repairing.

Bag Life

Bag life varies to a large extent depending on: dust characteristics, operating conditions, operating history (temperature surges, weld holes, embers), maintenance, and filter media characteristics.

SUMMARY

There is considerable interest in the use of filter media on high velocity outside collectors for coal-fired boilers. From our involvement in particulate control using fabric filters, we have learned the importance of good operating and maintenance procedures as well as the need for systematic problem solving techniques. Bags of Teflon® fiber have demonstrated good performance and long life which can often reduce operating and maintenance expenditures. Proper selection and use of bags can contribute to good operation.

REFERENCES

1. Anon., "The Side Stream Separator", General Motors Corp. (1980).
2. Lucas, R. L., "Gas-Solids Separations: State of the Art", Chemical Engineering Progress, 70, 52 (December 1974).
3. Barrosse, B. A., "Baghouses on Stoker-Fired Boilers", American Power Conference Proceedings, 37, 720 (1974).
4. McKee, D. E., et al, "A Review of Pulse Jet Baghouses and Dual Mechanical Collector Performance on Spreader Stoker-Fired Boilers", Paper No. 77-26.4, 1977 Air Pollution Control Association Annual Meeting, Toronto.
5. Smith, J. E., "Case History of Bag Filter Operation on Spreader Stoker Boilers", ASME Industrial Power Conference, Cleveland, OH, Oct. 23-26, 1977.
6. Bundy, R. P., "Operation & Maintenance of Fabric Filters", Journal of The Air Pollution Control Association, 30, 754, (July 1980).
7. Lucas, et al., "The Staclean™ Diffuser Increases Capacity and Reduces Bag Wear in Pulse-Jet Baghouses", Paper No. 80-30.4, 1980 Air Pollution Control Association Annual Meeting, Montreal.
8. ETS, Inc., "Fabric Filter Seminar Handbook".
9. Romanski, J. E., "Reducing Opacity by Optimizing Maintenance and Operating Procedures", Journal of the Air Pollution Control Association, 30, 748, (July 1980).
10. Rullman, D. H., "Baghouse Technology: A Perspective", Journal of the Air Pollution Control Association, 26, 16, (January 1976).

ACKNOWLEDGEMENTS

1. G. A. Faber and J. P. Fagan, E. I. du Pont de Nemours and Company, Inc., Fabrics & Finishes Department.
2. T. T. Gniewek and R. H. Mc Coy, E. I. du Pont de Nemours and Company, Inc., Chemical & Pigments Department.
3. G. P. Greiner, ETS, Inc.
4. A. S. Johnson, Jr., Staclean™ Diffuser Company.
5. R. L. Lucas, E. I. du Pont de Nemours and Company, Inc., Engineering Department.
6. J. N. Shah, E. I. du Pont de Nemours and Company, Inc., Textile Fibers Department.
7. R. J. Tessier, General Motors Corporation, Fisher Body Division.

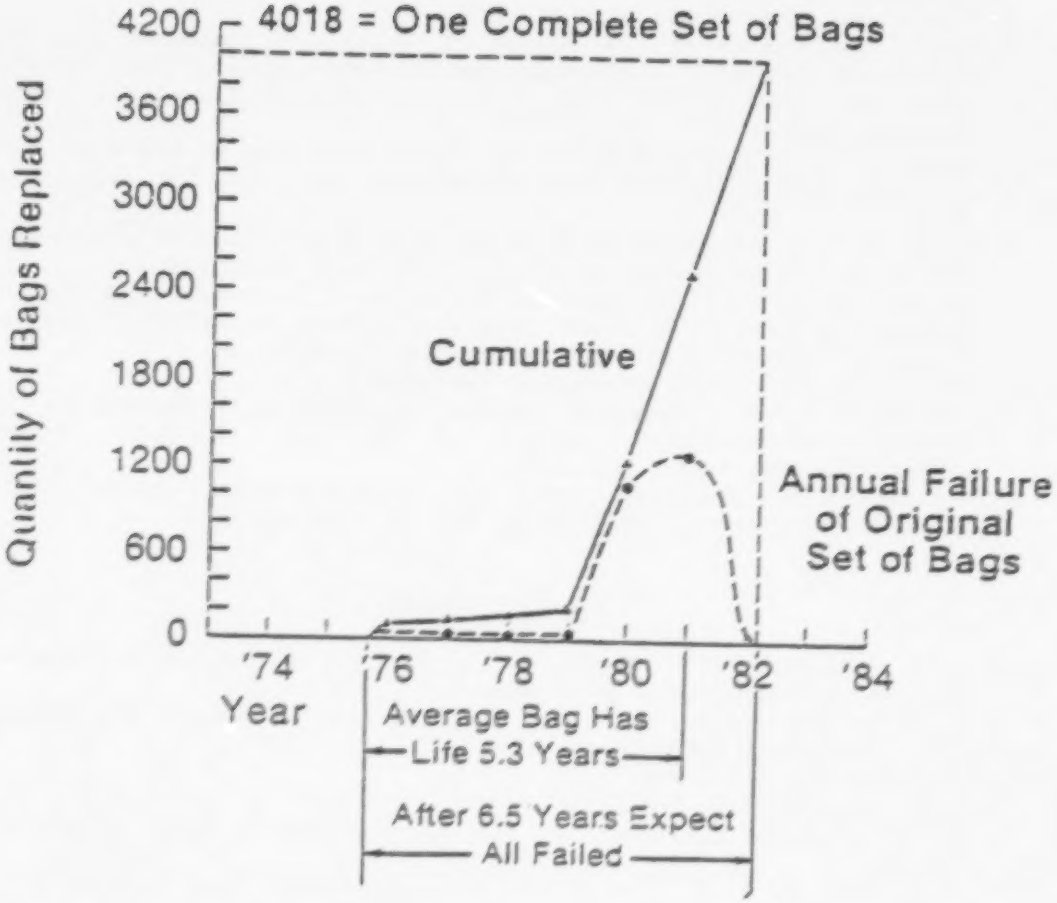


Figure 1

Bag Replacement at Du Pont West Virginia Plant

PILOT DEMONSTRATION OF THE PRECHARGER-COLLECTOR SYSTEM

By: P. Vann Bush and Duane H. Pontius
Southern Research Institute
Birmingham, AL 35255

ABSTRACT

Results from the evaluation of a 1000 ACFM pilot scale precharger-collector system in September, 1979 justified the development of a larger scale two-stage precipitator system. A pilot demonstration system with a 30,000 ACFM gas volume capacity was designed and fabricated, and it was installed at TVA's Bull Run Steam Plant. There is sufficient flexibility in the system to enable a thorough demonstration of the technology.

Continuous monitors interface to a computer data acquisition system to provide real-time mass efficiency, outlet particle size distribution, SO_2 concentration, and precipitator voltages and currents. These measurements will be supplemented with standard stack sampling techniques for selected precipitator conditions. Startup information and preliminary data as available at the time of the Symposium will be presented.

INTRODUCTION

Southern Research Institute (SoRI) has a contract with the EPA Industrial Environmental Research Laboratory (EPA/IERL) to demonstrate on a large pilot scale the precharger-collector system for high resistivity ash collection. The technical and economic feasibility of this two-stage design was confirmed by a small pilot scale system evaluation. SoRI contracted Lodge-Cottrell Division of Dresser Industries to design a two-stage electrostatic precipitator (ESP) system with a 30,000 ACFM gas volume capacity based upon the design of the small pilot scale system. Lodge-Cottrell was also contracted to fabricate and erect the pilot demonstration ESP.

The evaluation of the system performance will include a computerized continuous monitoring network. Component instruments in this automated data acquisition system are mass concentration monitors, particle size analyzer, SO_2 concentration monitor, total power consumption monitor, thermocouples, and voltage and current transducers. These instruments will be used to determine the optimum operating condition for the ESP. Once stable operation in this mode is achieved, supplemental measurements and analyses of the ESP system performance will be made using conventional stack sampling techniques.

DESIGN

The design of the pilot demonstration ESP was based upon the electrode design used in small pilot scale tests and standard ESP design practices. The precharger stage of the ESP is a three-electrode configuration patented by Pontius and Smith of SoRI. The arrangement of the three electrodes is shown schematically in Figure 1. Due to the proximity of the screen electrode to the grounded plate electrode and the necessity for separate high voltage sources for the screen and corona discharge electrodes, the design developed for the large pilot scale precharger had to incorporate techniques for fabricating and erecting the component parts within tolerances more restrictive than typical in ESP design.

The precharger stage has an active plate length in the direction of gas flow of 0.22m. The electrodes have an active height of 3.12m. There are eighteen gas passages in the precharger, with a plate-to-plate spacing of 0.18m, giving a total plate area of $24.7m^2$. A 50 kV, 50 mA power supply is used on the corona discharge electrodes which allows a maximum current density of 200 nA/cm^2. The screen electrodes are powered with a 20kV, 500 mA supply.

The collector stage of the pilot demonstration ESP was designed to allow flexibility in the type of discharge electrode used. Otherwise, the collector stage consists of four standard Lodge-Cottrell design electrical fields of 2.74m, 1.83m, 1.83m, and 2.74m lengths. There are three rapping fields, with fields two and three sharing 3.66m long collection plates. The plate height in all fields is 3.12m. There are thirteen gas passages in the collector stage, with a plate-to-plate spacing of 0.25m, giving a total collection plate area of $742.8m^2$. Each electrical field is energized with a transformer-rectifier set having a capacity of 55 kV and 200 mA.

The discharge electrode designs selected for study in the collector stage are 2.5 cm mesh x 0.32 cm diameter wire mounted on standard Lodge-Cottrell masts and 0.95 cm diameter rods spaced 9.2 cm apart on standard Lodge-Cottrell masts. These special configurations were selected for their abilities to produce a low, stable current at a high voltage, which is a desirable feature for the collector stage of a two-stage ESP.

A flow model study was conducted by Lodge-Cottrell to assist in the design of flow distribution splitters for the inlet nozzle to the ESP, baffles between sections, and the flow straighteners in the inlet and outlet. The flow model was built at one-half scale which allowed greater precision in developing design parameters than typical of full-scale units which are modeled at one-sixteenth or one-eighth scale.

The internal arrangement of the precharger-collector system is shown in the schematic sectional side view in Figure 2.

INSTALLATION

The pilot demonstration ESP system was installed at the TVA Bull Run Steam Plant. This plant was chosen because the coal source used provides a consistent grade low-sulfur coal which produces a high resistivity ash ($5x10^{11}$ohm-cm at

130°C). Combustion exhaust gases are extracted immediately downstream of the air preheater, pulled through the pilot scale system, and reentered into the plant duct. A schematic illustration of the pilot demonstration site arrangement is given in Figure 3.

The collector-stage electrodes were installed in the ESP casing and then aligned. The 0.95 cm diameter rod discharge electrode masts were installed in the four collector fields. Standard Lodge-Cottrell design cam-type drop rods are used for electrode rapping in the collector sections.

The precharger electrodes were assembled on temporary scaffolding outside the ESP casing. This made it easier to properly align the three-electrode arrangement. The assembled precharger was set into the ESP casing and final alignment of the electrodes was performed. The electrode spacing tolerances were not difficult to attain due to the careful fabrication and treatment of the electrodes. Electric vibrators are used to provide ash removal from the precharger electrodes.

The Laboratory/Control Building for the pilot demonstration ESP is represented in Figure 3. The control panels for the transformer-rectifier sets, the power supply controls for the precharger stage, precharger vibrator control panel, rapper controls, hopper controls, and power distribution panels are located in the building. Also, the minicomputer used for the precharger-collector system evaluation is in the laboratory.

EVALUATION

A computerized data acquisition system is used to monitor long-term operating stability and the effects of changes in the system operating values. The secondary voltage and current values from each of the transformer-rectifier sets and from the precharger power supplies are monitored. A wattmeter is used to log total power consumption. A P-5A Particulate Monitor made by Environmental Systems Corporation is installed in the ESP inlet ductwork to measure the inlet mass loading. Another P-5A Particulate Monitor is located in the outlet ductwork to measure the outlet mass loading. Thermocouples are used to monitor inlet and outlet flue gas temperatures. A Lear Siegler SO_2 monitor measures the SO_2 concentration in the flue gas; which, together with the temperature, can be used to detect a possible change in the ash resistivity. A Fine Particle Stack Spectrometer System (FPSSS) by Particle Measuring Systems is installed in the outlet ductwork to monitor the particle size distribution.

These continuous monitors are interfaced to a PDP 11/23 minicomputer. A block diagram of the data acquisition system is shown in Figure 4. A data handling program has been developed which acquires data from the monitors, checks the integrity of the data, stores the acquired data on diskettes, computes mass efficiency from the two P-5A monitors, displays selected data, and plots the data if desired. The frequency and number of data samples are selectable. The computer monitor continuously displays an updated summary of the data record.

STARTUP INFORMATION

The startup of the precharger-collector system consisted of primarily six phases: collector stage rapping check, precharger vibrator sequencer programming, transformer-rectifier checkout, precharger power supply checkout, hopper heater/ash disposal system check, and monitor data acquisition check. There were no difficulties in energizing and operating the collector stage rapping and transformer-rectifier sets. The precharger vibrators were programmed and activated. The hopper heaters were turned on and the thermostatic controls set. The ash disposal system which was integrated into the plant system was modified to improve the operation.

As expected in a prototype system, the precharger startup was not as straightforward as the collector stage startup. One of the precharger power supplies was incorrectly wired. This has since been corrected. The collector stages and the data acquisition system have been operated. We have not been operating long enough to present any data at this time.

We plan to operate the system continuously for several weeks before a complete characterization of performance is made, since long-term operating experience and an assessment of reliability are essential components of the ultimate evaluation of the system.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Morey Nunn of Lodge-Cottrell for his technical management of the design, fabrication, and erection of the pilot demonstration ESP.

We appreciate the work of William Steele and Bobby Pyle of SoRI in the development of the data acquisition programs.

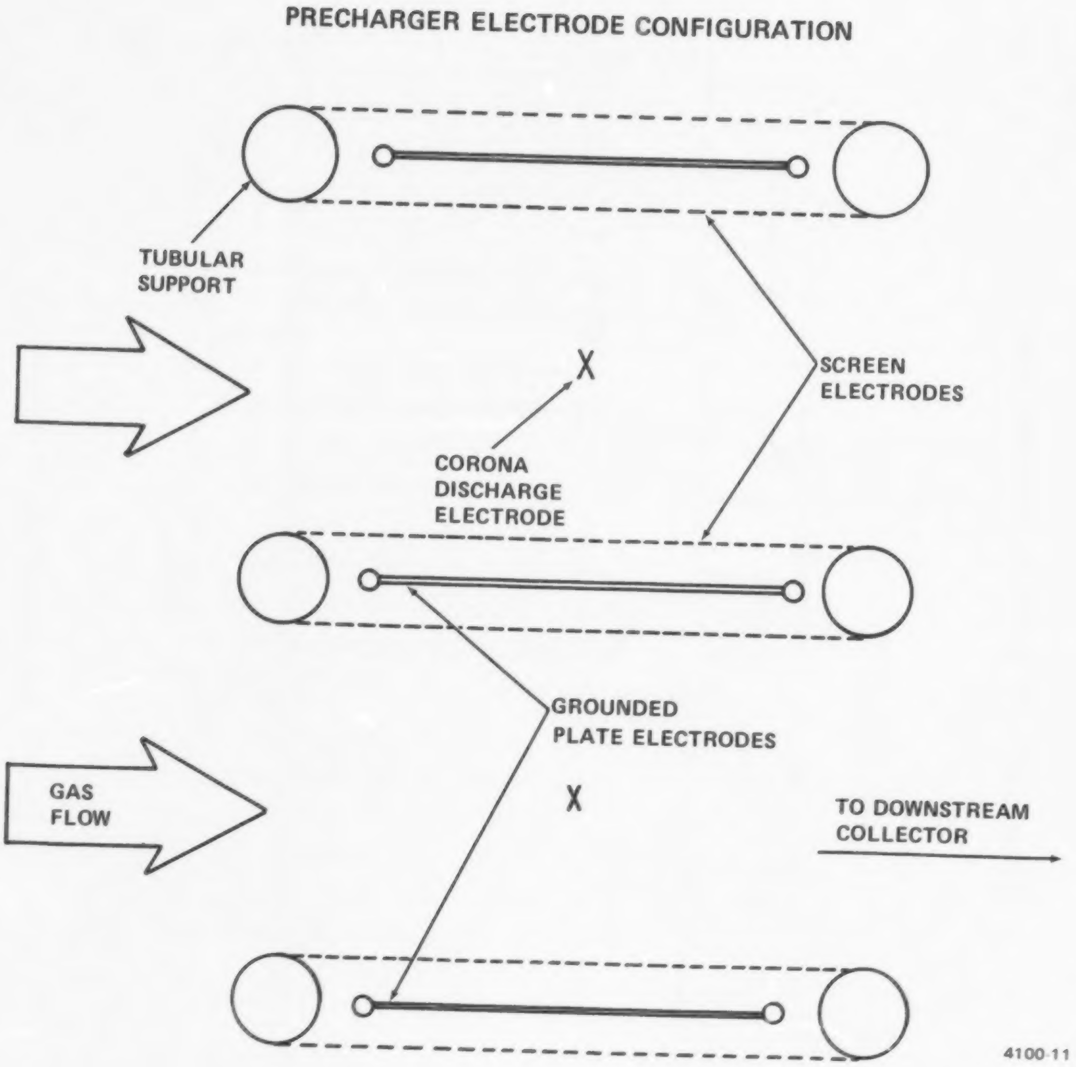

PRECHARGER ELECTRODE CONFIGURATION
TUBULAR SUPPORT
SCREEN ELECTRODES
CORONA DISCHARGE ELECTRODE
GROUNDED PLATE ELECTRODES
GAS FLOW
TO DOWNSTREAM COLLECTOR
4100-11

Figure 1. Precharger electrode configuration.

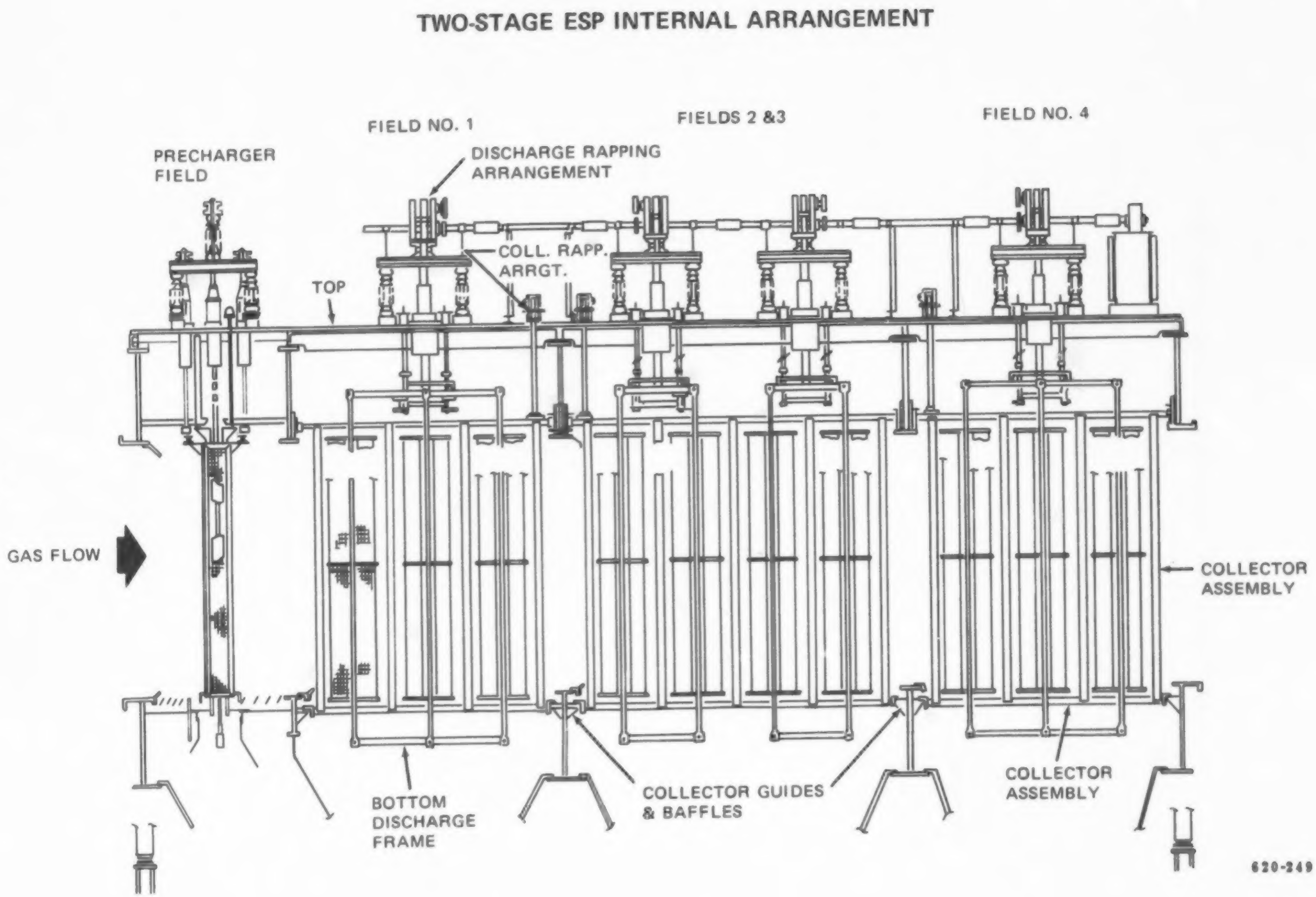

TWO-STAGE ESP INTERNAL ARRANGEMENT
FIELD NO. 1
FIELDS 2 &3
FIELD NO. 4
PRECHARGER FIELD
DISCHARGE RAPPING ARRANGEMENT
COLL. RAPP. ARRGT.
TOP
GAS FLOW
COLLECTOR ASSEMBLY
BOTTOM DISCHARGE FRAME
COLLECTOR GUIDES & BAFFLES
COLLECTOR ASSEMBLY
620-249

Figure 2. Two-stage ESP internal arrangement.

PILOT DEMONSTRATION ESP FACILITY

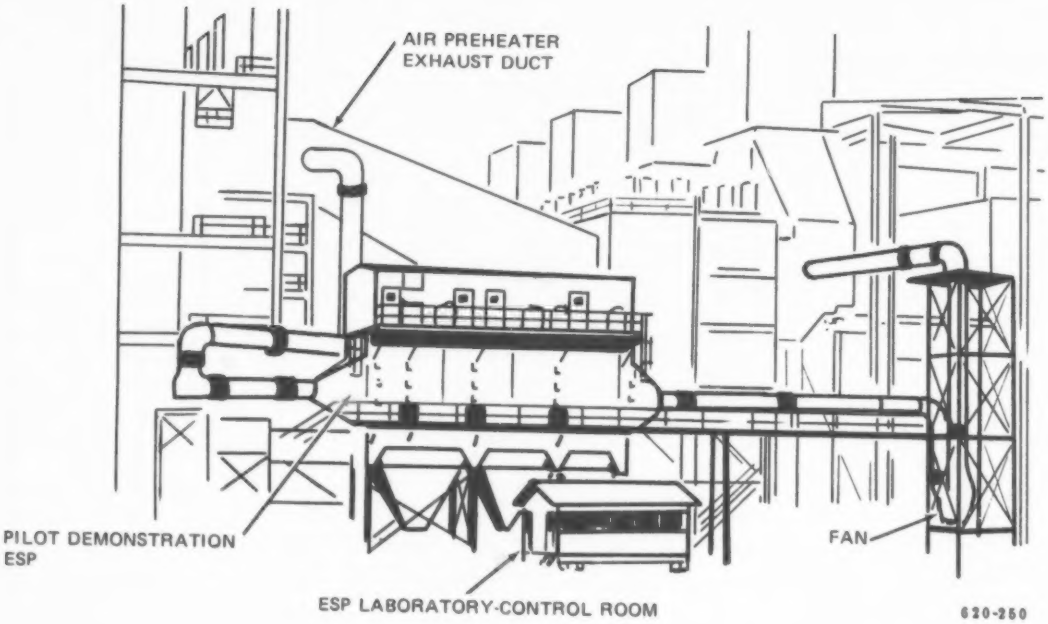

AIR PREHEATER EXHAUST DUCT
PILOT DEMONSTRATION ESP
FAN
ESP LABORATORY-CONTROL ROOM
620-250

Figure 3. Pilot demonstration ESP facility.

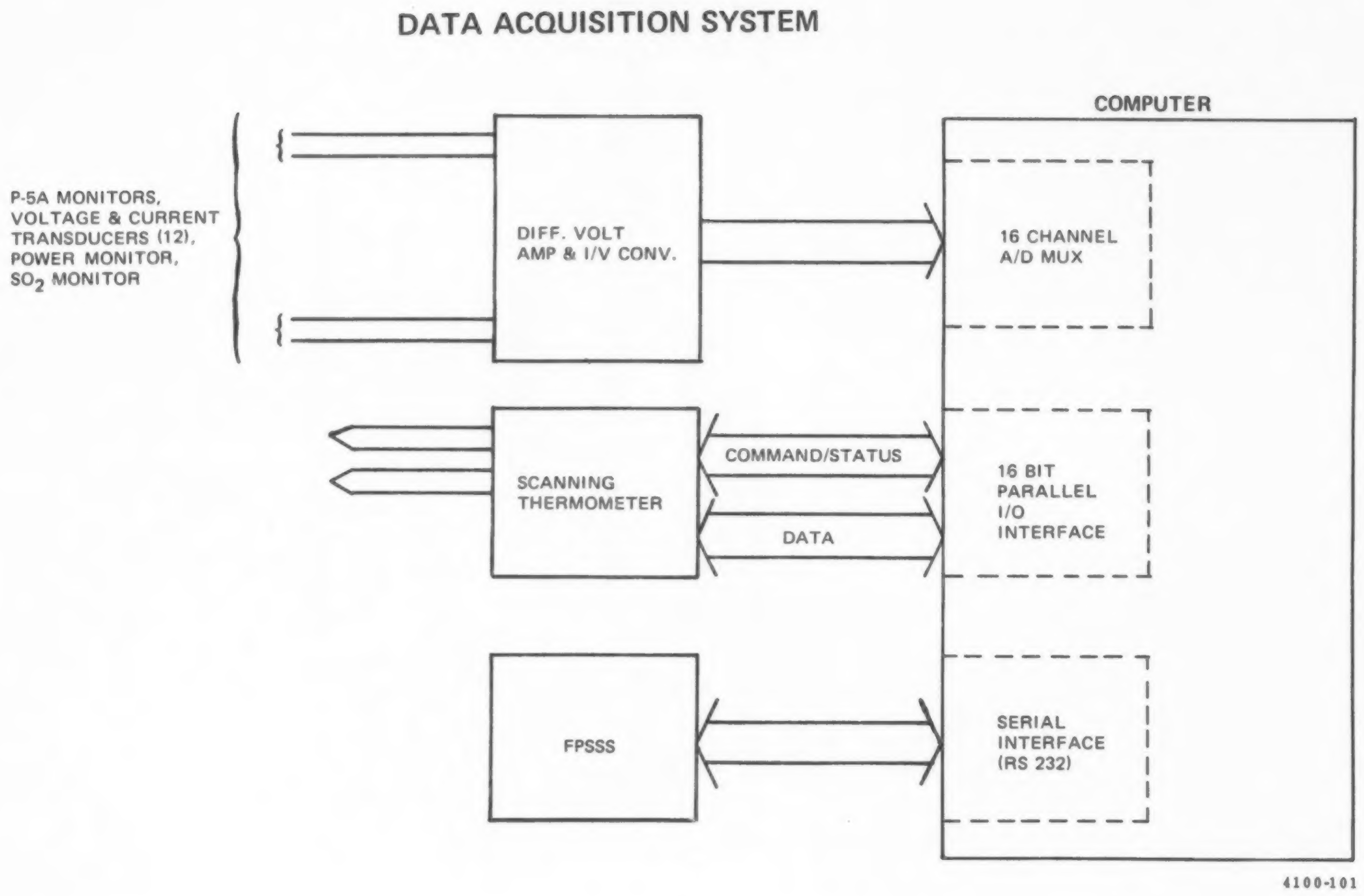

DATA ACQUISITION SYSTEM
P-5A MONITORS, VOLTAGE & CURRENT TRANSDUCERS (12), POWER MONITOR, SO_2 MONITOR
DIFF. VOLT AMP & I/V CONV.
SCANNING THERMOMETER
FPSSS
COMMAND/STATUS
DATA
COMPUTER
16 CHANNEL A/D MUX
16 BIT PARALLEL I/O INTERFACE
SERIAL INTERFACE (RS 232)
4100-101

Figure 4. Block diagram of the data acquisition system.

REMEDIAL TREATMENTS FOR DETERIORATED HOT SIDE PRECIPITATOR PERFORMANCE

By: Roy E. Bickelhaupt
Southern Research Institute
Birmingham, Alabama 35255

ABSTRACT

Laboratory experiments with parallel plate resistivity cells were conducted to provide chemical evidence in support of the sodium depletion phenomenon as the cause of time dependent deterioration of hot side precipitator performance. Using a wire/plate corona discharge device with hand-placed untreated and sodium conditioned ash, the effect of commercial sodium conditioning was successfully recreated in the laboratory. Chemical analyses and current density/time relationships suggest that the conditioning effect occurs because sodium from the conditioned ash diffuses chemically toward the collection plate into the zone depleted of sodium. Apparently an equilibrium is established between sodium chemically diffusing toward the plate and sodium migrating away from the plate under the influence of the electric field. Collection plate doping was found to be a potential remedial treatment. This technique involves placing a substance having a high concentration of charge-carrying ions on the steel plate to relieve the blocking effect of the collection electrode. A thin layer of high sodium, borosilicate glass simulating a porcelain enameled plate and a film of sodium carbonate dried from an aqueous solution worked well.

INTRODUCTION

One of the techniques used to combat the problem of high resistivity fly ash is to install the electrostatic precipitator on the hot side of the air preheater. At the typical hot side temperature of 350°C, almost all fly ashes have a resistivity lower than 1×10^{11} ohm cm. Therefore, with an adequately designed hot side precipitator, one expects to be able to burn low sulfur coal without the need for flue gas conditioning and without concern about fly ash compositional variations.

A large number of hot side precipitators have been in service for several years. One of the most difficult problems encountered is the deterioration of performance as a function of time. This has occurred even though the precipitator design, construction, and operation are properly executed. As the performance deteriorates, the electric power to the precipitator attenuates, and the current/voltage relationship suggests back corona. Back corona is a manifestation of dielectric breakdown of the collected ash layer due to intense electric fields caused by excessively high resistivity. Inconsistently, in-situ and laboratory resistivity measurements indicate that back corona should not occur.

In a previous paper(1) an interpretation of the observed phenomenon was given. It was suggested that a thin layer of fly ash tenaciously adheres to the surface of the collection plate even though a good rapping schedule is followed. After a long time under electric stress, the thin layer is depleted of mobile charge carriers, sodium ions. Current flow through the fly ash layer is greatly attenuated, because conduction is then dependent on a different, less favorable mechanism. The thin, more-or-less permanent ash layer develops a high resistivity, and consequently, the collection plate surface becomes coated with a very good electric insulator.

To overcome this problem, the formation of the tenaciously adherent layer must be prevented, or a source of charge-carrying ions must be made available to the sodium depleted zone. This paper describes the results of laboratory experiments conducted to better understand the phenomenon and to evaluate several remedial techniques.

CHEMICAL EVIDENCE OF THE SODIUM DEPLETED LAYER

Evidence(2) obtained with chemical transference experiments to demonstrate ionic conduction showed an increase in sodium at the cathode and a decrease in sodium at the anode. However, these experiments could not illustrate the very steep sodium concentration gradient suggested in reference 1 for the ash contiguous with the electrodes, because the thickness of the ash layers chemically analyzed were too great. Attempts have been made to show the sodium gradient using fly ash removed from commercial precipitator collection plates. While it is found that the sodium concentration in the ash layer decreases as the collection plate surface is approached, the very steep gradient cannot be shown. Several reasons are suggested to explain this.

One argument is that the very thin layer depleted of sodium becomes intermixed with the oxidation/corrosion product on the collection plate surface. It is very difficult to remove successive 50 to 100 micron thick layers of ash from a collection plate and maintain the cut parallel to the metal plate. It is also conceivable that sodium can migrate back toward the depleted zone because: a) the plates remain hot without power to the precipitator at the start of a shutdown, or b) the high ambient relative humidity during shutdown facilitates reverse migration. It is believed that operators have noted improved performance resulting from a short shutdown because of the above factors.

To demonstrate the substantial depletion of sodium in an ash layer contiguous with the anode (collection plate), several experimental prerequisites must be met to overcome the specific points mentioned immediately above. Two stainless steel electrodes were fabricated with recesses 0.01 cm and 0.02 cm deep in the anode and cathode surfaces, respectively. Large fly ash particles and strong agglomerates of particles would present a problem when only the ash contained in the recess was to be removed. Therefore, the fly ash was passed through a 200 mesh screen before use. The minus 200 mesh ash contained 0.34 percent sodium expressed as oxide in weight percent. A 0.4 cm layer of this ash was placed between the described electrodes.

To make sure that a significant chemical change occurred within the ash layer in a reasonable time, the experiment was conducted at 470°C (880°F) in an environment of air containing 1 percent mositure. The ash layer was maintained under a voltage gradient of 5 kV/cm for 7 days. Conducting the experiment near the upper end of the hot side precipitator temperature range produced a high current density that caused the depleted zone to develop quickly. To transport the same quantity of electric energy at about 350°C would require in excess of 70 days, an undesirable laboratory situation.

Current density as a function of time of applied voltage gradient is shown in Figure 1. This curve shape is typical for the current density/time relationship during which sodium depletion takes place. The initial part of the curve probably represents the time during which a dimensionally stable layer of sodium depleted ash is developed. Later the charge transport through the depleted zone is dependent on a mechanism other than sodium migration, and the current density asymptotically approaches an equilibrium value for this mechanism. If the anode (collection plate) were capable of injecting carrier ions into the contiguous fly ash and the cathode were a nonblocking electrode, the observed current density attenuation would not occur.

The resistivity values shown in Figure 1 are from calculations made at the start and termination of the test. The 2.5×10^{10} ohm cm value shown for the 0.4 cm ash layer at the end of the test is the effective resistivity for several resistances in series. The most influential resistance in this series is the sodium depleted zone.

After completing the test, the ash layer was cooled under electric stress in dry air. The ash contained in the recessed faces of the electrodes was quickly removed for chemical analysis. The 0.01 cm layer of ash contiguous with the anode contained 0.06% sodium as oxide in weight percent, and the 0.02 cm layer adjacent to the cathode contained 0.77%. These data are plotted as part of a hypothetical sodium concentration profile in Figure 2. For lack of data, the exact profile is not known. However, based on other investigations, it seems correct that the curve should pass through the coordinates 0.25% sodium oxide and 0.25 millimeters and that the composition at the centerline should be equal to the starting composition. This is the expected profile for an ionic conduction process operating with a fixed number of mobile charge carriers between blocking electrodes. In a precipitator showing performance deterioration, the rapping process dislodges all of the ash layer except some fraction of a millimeter nearest the collection plate or anode.

Two somewhat crude but interesting calculations can be made using these data. Assuming that sodium is the only conducting species with respect to all the electric energy passed in Figure 1, about 5 x 10^{-5} grams of sodium per cm^2 of electrode area would have migrated out of the ash layer contiguous with the anode. Considering the subtle factors such as the ash layer porosity, it was computed that the 0.01 cm thick ash layer contained about 4 x 10^{-5} grams of sodium per cm^2. This suggests that all of the mobile sodium in the recessed ash layer migrated.

Assume that the terminal resistivity of 2.5 x 10^{10} ohm cm was the resultant for two uniform layers. One layer has a thickness of 0.01 cm and an unknown resistivity, while the other layer has a resistivity of 1.3 x 10^9 ohm cm and thickness of 0.39 cm. From these data and assumptions, the resistivity of the thin, sodium depleted zone is calculated as about 1 x 10^{12} ohm cm. If this experiment had been conducted for a much longer time at a conventional hot side temperature of 350°C, the computed resistivity value for the depleted zone would be about 1 x 10^{13} ohm cm. In a precipitator, the situation is additionally aggravated by lower temperatures prevailing when the power generating system is not at full load and especially during the time that the unit is being brought to full load.

RESULTS USING REMEDIAL TECHNIQUES

Reversable Polarity

In reference 1, several remedial techniques were suggested to overcome the degraded precipitator performance caused by the development of a sodium depleted layer of ash. One of the principal experimental techniques used to define the character of the sodium depletion phenomenon was polarity reversal. It was shown that a degraded current density/voltage relationship created with a given polarity could be caused to recover by reversing the corona polarity. Subsequently this technique was attempted in the field using commercial equipment. The results were negative, and the tests terminated. In principal the procedure has merit; however, the conventional precipitator designed for negative corona is incapable of operating under positive polarity(3).

Sodium Conditioning

Another remedial technique that has received commercial application is sodium conditioning. Apparently some success has been obtained by injecting dry sodium compounds into the ductwork preceding a hot side precipitator(4). On the other hand, a totally negative result was obtained when this technique was tried with a cold side precipitator(5).

During the past year, sodium conditioning by the addition of a sodium compound to the coal feed has been investigated, and an interim report has been published(6). It was found that the sodium compound decomposed and/or volatilized in the furnace and the vapor condensed on the fly ash surface becoming an integral part of the ash. When this conditioned ash was precipitated on top of the thin, sodium depleted ash layer adhering to the collection plates, an interesting result occurred. The effect is shown in Figure 3 where total power to the precipitator and the particulate emission rate are illustrated as a function of time.

Precipitator washing is a common technique to obtain relief from the sodium depletion problem for a short time, perhaps up to 60 days. Although the washing operating does not necessarily remove the fly ash that is tenaciously adherent to the oxidized surface of the mild steel collection plate, the procedure apparently promotes the movement of sodium ions back toward the collection plate. The water, penetrating the adherent layer, carries sodium in solution or increases the surface diffusion of the sodium toward the plate. It is believed that this is what occurs when a precipitator is shut down and exposed to ambient conditions. The shutdown usually results in improved performance for a very short time.

In Figure 3 it is shown that 50 days after washing, the precipitator power had decreased an order of magnitude and the emission rate approached 0.3 lbs/10^6 BTU. At that point, sodium conditioning was started, and within a few days, the power to the precipitator had increased about 5 times and the emission rate was less than 0.05 lbs/10^6 BTU. This significant recovery occurred even though the collection plate surfaces were covered with a thin layer of sodium depleted ash. It would seem improbable that sodium-rich, conditioned ash could penetrate the interstices of the sodium depleted layer to provide a source of sodium at the plate. Therefore, it was assumed that sodium from the conditioned ash chemically diffused toward the collection plate.

After some period of time with a given level of sodium conditioning, the performance characteristics are apparently controlled by an equilibrium established between two competing processes. On the one hand, sodium ions serving as charge carriers are motivated away from the collection plate under the influence of the electric field created in the ash layer. On the other hand, sodium ions from the surface of the sodium-rich, conditioned ash migrate toward the collection plate under the influence of the negative gradient of the chemical potential, i.e., the difference in sodium concentration between the conditioned ash and the sodium depleted ash. The chemical diffusion idea is especially plausible since the increased sodium concentration for the conditioned ash is associated with the ash surface thereby offering potentially high diffusivity coefficients.

A laboratory experiment was conducted to: a) determine whether the data shown in Figure 3 could be reproduced in the laboratory and b) determine whether the chemical diffusion of sodium into the depleted zone could be detected. A previously described wire/plate corona discharge device (7) that utilizes a 0.5 cm layer of hand-placed ash was used. An ash containing 0.32% sodium by weight as oxide was placed on the plate and a negative 11 kV voltage was applied. After 264 hours, the current density/time relationship shown in Figure 4 as Phase 1 was established. At this point, the ash layer was cooled in the dry air environment, removed from the test chamber, and while still hot to the touch, the plate was placed on edge and gently tapped.

About 0.5 mm of ash adhered to the "collection plate". This was quickly overlayed with conditioned ash containing 1.8% sodium by weight as oxide and returned to the test apparatus. The assembly was quickly heated to 345°C in dry air, and the negative 11 kV voltage was reapplied. That portion of Figure 4 labeled Phase 2 was then generated.

It is obvious that the combination of Phase 1 and Phase 2 in Figure 4 produces the same curve shape as that for precipitator power versus time in Figure 3. In Figure 4, the solid symbols represent the actual data taken. It is believed that the offset in the data was due to experimental problems related to starting and stopping the experiment and removing and replacing ash by hand. The dashed curve simply shows the data as if the offset had not occurred.

In a companion experiment, the 0.5 mm layer of ash adhering to the "collection plate" at the end of Phase 1 was removed for chemical analysis rather than overlayed with conditioned ash. This adherent layer had a sodium content of 0.29% by weight as oxide in contrast to the 0.32% determined for this ash prior to the test. Chemical analysis of the 0.5 mm layer of ash contiguous to the "collection plate" at the end of the experiment involving the overlay of conditioned ash (Phase 2) revealed a sodium concentration of 0.39%. A very significant difference in percent of combustibles between the original ash and the overlayed, sodium conditioned ash gave evidence that it was unlikely that mechanical mixing of the two ash layers provided the chemical change determined for sodium concentration.

The described experiment illustrated three important points. First, overlaying a sodium depleted ash layer with a second layer of ash that had received a surface enrichment of sodium by conditioning caused current density to increase even though a voltage was continuously applied. Second, the current density increased at a decreasing rate for three days as it approached a limit value. Third, chemical analyses suggest the sodium concentration in the sodium depleted zone increased slightly due to the sodium-rich, overlayed ash.

Since the positive electrode, "collection plate", was at all times covered with a continuous layer of sodium depleted ash and there was no conceivable way for the conditioned ash to penetrate this layer, it is concluded that the sodium from the conditioned ash chemically diffused into the sodium-depleted zone. Apparently, it required about three days for the competing processes, inward sodium migration due to chemical diffusion and outward migration due to electric field polarity, to equilibrate under the particular set of circumstances.

Collection Plate Doping

Since a steel collection plate cannot furnish or give up sodium ions to an adherent ash layer, it is called a blocking electrode and electrode polarization occurs under negative corona. If the collection plate possessed an unlimited source of sodium or other mobile charge-carrying ions, the electrode blocking effect and the time dependent attenuation of current density would not occur. It is believed that the time dependent deterioration of cold side precipitator performance is not common because there usually is an unlimited source of alternate charge carriers, adsorbed sulfuric acid vapor.

It follows that a source of charge carriers provided to the collection plate should overcome the effect of the blocking electrode. Therefore, several laboratory experiments were conducted to evaluate the effect of collection plate doping; i.e., providing the collection plate surface with a large quantity of charge carriers. This was done in two ways: a) an aqueous solution containing 10 percent sodium carbonate was allowed to evaporate on an electrode surface leaving a white film, and b) a 200-micron-thick layer of minus 325 mesh borosilicate glass containing 16.8% sodium as oxide in weight percent was placed in a position contiguous with an electrode surface.

Three experiments were conducted using a parallel plate resistivity cell. In each case a voltage of 2 kV was continuously applied to a 0.4 cm layer of fly ash that contained 0.34% sodium by weight as oxide. The test cell was maintained at 470°C in an air environment containing 1% water vapor. Anode conditions evaluated included clean stainless steel surfaces and the two doped surfaces described above.

Current was monitored as a function of time of applied voltage, and these data are given in Figure 5. In each case for a very short time, the current increased. This could be due to the establishment of good particle contact and/or the migration of the carrier ions located in most favorable positions. The rapid and pronounced attenuation of current with time for the electrode set without doping is typical for the voltage applied and the test temperature. In 7 days, the current decreased by a factor of 20. Doping the anode surface with either a thin layer of high sodium glass or a film of sodium carbonate caused a great reduction in the rate at which the current/time relationship decreased.

The thin layer of pulverized glass represented a simulation of a high sodium porcelain enamel coating on a steel collection plate. After 132 hours, the current flowing through this composite of 0.02 cm of glass and 0.38 cm of ash was still over an order of magnitude greater than the current flowing in the undoped specimen. The effect would be even more pronounced if the test were run using constant current density instead of constant applied voltage.

In the case of doping with sodium carbonate, an attempt was made to simulate the effect of ending a precipitator washing operation by saturating the adherent ash layer with a 10% aqueous solution of sodium carbonate. This procedure caused a great change in the current/time relationship. After 180 hours, the current flowing through the layer doped with sodium carbonate was almost 50 times as great as the current passing through the ash layer with no doping. Assuming that the current/time relationship for the sodium carbonate doping experiment would eventually develop the same curve shape as the other two curves shown in Figure 5, one would anticipate that this remedial technique would be required on a very infrequent basis.

To demonstrate that the desirable effect due to the deposition of a thin film of sodium carbonate on the anode was truly related to sodium migration, a 0.02 cm layer of ash contiguous with the cathode was chemically analyzed after the 180 hour test was completed. This sample of ash, which at the start of the test contained 0.34% sodium as oxide in weight percent, now contained 4.5% sodium.

The effect of collection plate doping was also evaluated using a wire/plate corona discharge device. A layer of minus 325 mesh borosilicate glass 0.01 cm thick was placed on the "collection plate" and was covered with 0.49 cm of low sodium ash. Current density was determined as a function of time for a voltage of -10 kV in dry air at 372°C.

After 132 hours, the current density had decreased from an initial value of 81 nA/cm^2 to 50 nA/cm^2 for an experiment without doping. In the same time period, the current density had increased about 20% for a similar test with doping.

CONCLUSIONS

- To accompany previously described electrical data, chemical evidence has been obtained to demonstrate the depletion of sodium in a thin layer of ash contiguous with a positive electrode. From the data acquired, one can calculate that the resistivity of this thin layer of ash can be in excess of 1×10^{13} ohm cm under certain conditions.

- A laboratory experiment to simulate the effect of sodium conditioning in a hot side precipitator has been successfully executed. These data suggest that sodium enriched fly ash collected on top of a sodium depleted ash layer conditions this high resistivity material by the chemical diffusion of sodium ions toward the collection plate.

- Laboratory experiments indicate that electrode doping, supplying the collection electrode surface with a source of charge-carrying ions, is a potential remedial procedure to overcome the problem of time dependent precipitator performance loss.

ACKNOWLEDGMENT

Funds for this research were principally supplied by Southern Company Services, Inc., the Electric Power Research Institute. and the U. S. Environmental Protection Agency.

ENDNOTES

1. R. E. Bickelhaupt, "An Interpretation of the Deteriorative Performance of Hot-Side Precipitators," JAPCA 30:882 (1980).

2a. R. E. Bickelhaupt, "Electrical Volume Conduction of Fly Ash," JAPCA 24:251 (1974).

2b. R. E. Bickelhaupt, "Volume Resistivity-Fly Composition Relationship," ENVIRON. SC. TECH 9:336 (1975).

3. Private communication with G. B. Nichols, Southern Research Institute.

4. P. B. Lederman, P. B. Bibbo, and J. Bush, "Chemical Conditioning of Fly Ash for Hot-Side Precipitation," EPA-600/7-79-044a, pp 79-98, Environmental Protection Agency, Research Triangle Park, NC, February 1979.

5. J. P. Gooch, R. E. Bickelhaupt, and L. E. Sparks, "Fly Ash Conditioning by Co-Precipitation with Sodium Carbonate," EPA-600/9-80-039a, pp 132-153, Environmental Protection Agency, Research Triangle Park, NC, September 1980.

6. J. P. Gooch, et al, "Improvement of Hot-Side Precipitator Performance with Sodium Conditioning - An Interim Report," JAPCA 31:   (1981).

7. R. E. Bickelhaupt, "High Resistivity Behavior of Hot-Side Electrostatic Precipitators," EPA-600/7-80-076, Environmental Protection Agency, Research Triangle Park, NC, April 1980.

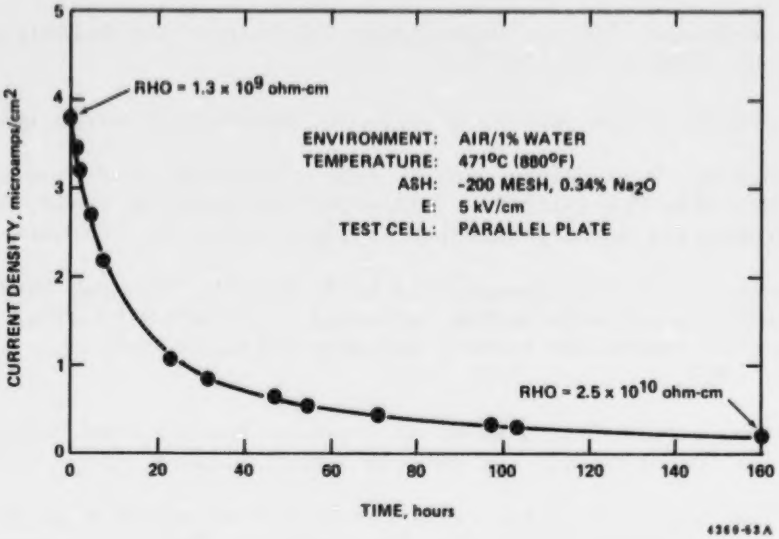


Figure 1. Current density vs. time of applied voltage.

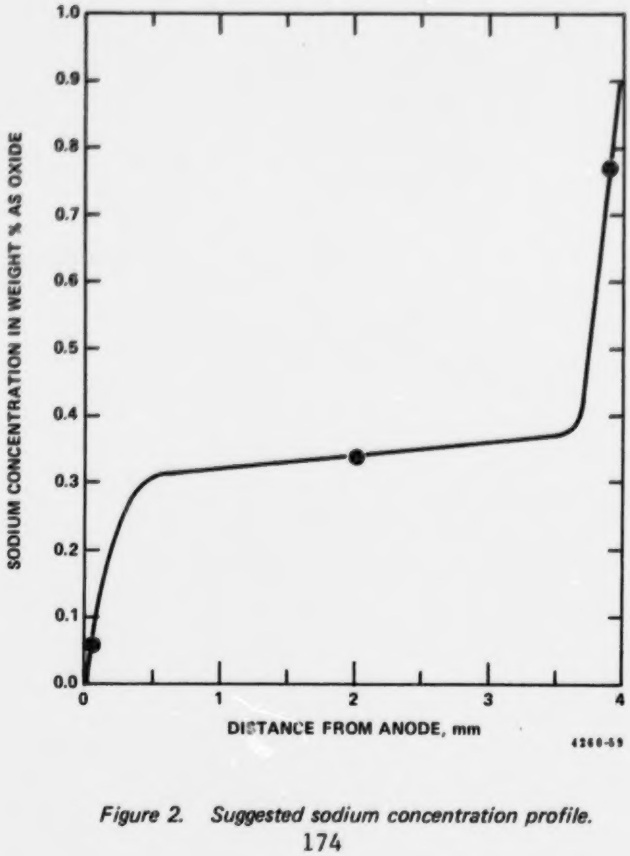


Figure 2. Suggested sodium concentration profile.

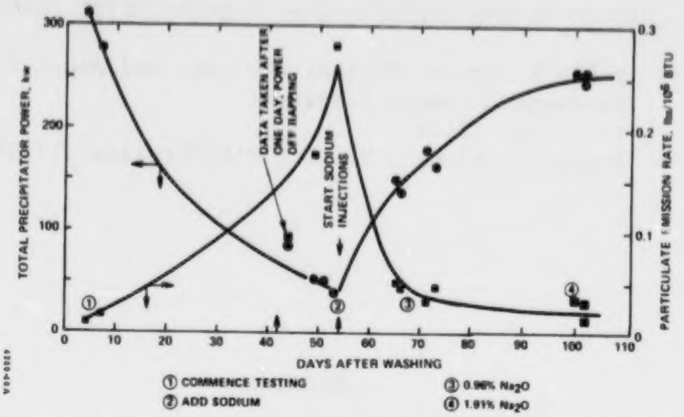


Figure 3. *Chronological display of Lansing Smith Data. Data taken from hot-side ESP which is followed by a cold-side ESP (from Reference 6).*

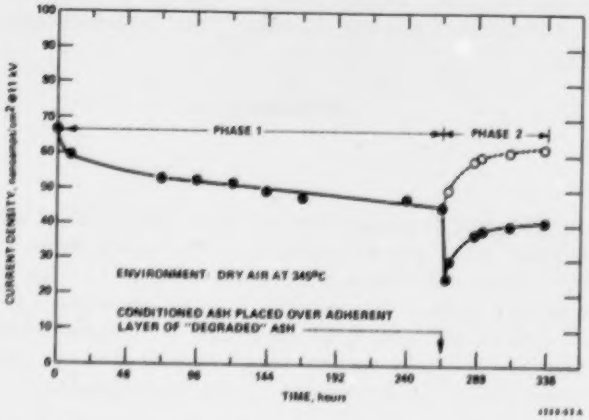


Figure 4. *Laboratory simulation of the effect of sodium conditioning.*

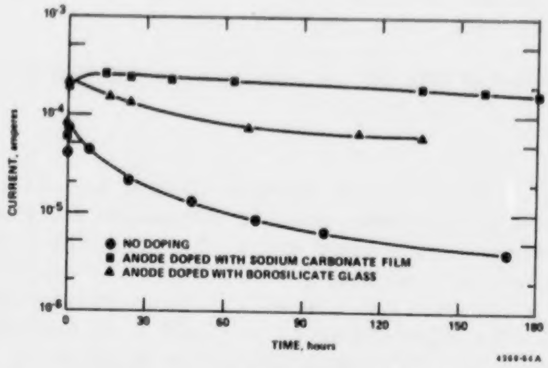


Figure 5. *Effect of anode doping on attenuation of current/time relationship.*

EVALUATION OF THE UNITED McGILL ELECTROSTATIC PRECIPITATOR

By: David S. Ensor, Phil A. Lawless, and Ashok S. Damle
Research Triangle Institute
P. O. Box 12194
Research Triangle Park, North Carolina 27709

ABSTRACT

A United McGill electrostatic precipitator installed on an industrial coal-fired boiler was evaluated during a field test. Included in the testing were measurements of particle size distribution from 0.05 to 10 μm diameter, opacity, mass concentration, resistivity, and plant parameters. The particle size dependent efficiency, rapping losses, and power requirements are reported for the unit.

INTRODUCTION

Objective

The objective was the evaluation of the technology associated with the United McGill electrostatic precipitator. The data were used to develop a computer model describing the specific conditions in the precipitator. A secondary objective not reported in this paper because of its exploratory nature was the development of new test methods to characterize the flow distribution in precipitators. This paper reports the overall performance of the precipitator and the particle size distribution results.

Background

The United McGill is a precipitator of innovative design. Energized plates rather than wires are used for discharge electrodes. The unusual design motivated a two-week field test program.

DESCRIPTION OF THE ELECTROSTATIC PRECIPITATOR

Design

The precipitator consists of rows of plates parallel to the direction of gas flow. Alternate plates have needles installed on the leading and trailing edges. These points act as corona sites when the plate is energized. The other plates are grounded and act as collectors. Both the energized and grounded plates are rapped from the side. Specific design features are listed in Table 1. The plate spacing of 0.08 m is much narrower than conventional precipitators. The precipitator is modular in design. It is fabricated in sections at a central manufacturing facility and assembled at the site.

Site

The precipitators were installed on an industrial boiler fired with eastern subbituminous coal. The coal typically was 12 percent ash, two percent sulfur, and had a heat value of 12500 BTU/lb. Two separate precipitators were installed in parallel with installation gate valves at each inlet. During the tests, the boiler load was low enough to allow diversion of all the flue gas through one precipitator.

TEST METHODS

Overview

A series of comprehensive test methods were used during a two-week field test. However, no compliance test methods were used. The particle size distribution and the charge-to-mass ratio of ash entering and leaving the precipitator were determined. Supporting measurements included: ash resistivity, flue gas sulfur oxides, boiler operation, and precipitator controls.

Size Distribution

The size distribution was measured with cascade impactors for particle diameters greater than 0.5 μm and with electrical aerosol analyzers and optical particle counters for particles less than 5 μm diameter. The Meteorology Research, Inc., Model 1502 Cascade Impactor was used at both the inlet and outlet of the precipitator. Generally, the procedures described by Wilson(1) were followed. Short sampling times of about one minute were used at the inlet. One half of the jet holes on the last stage of the impactors used in the inlet tests were blocked to reduce the particle size cutoff by 40 percent. The outlet impactor tests were conducted for about two hours to obtain weighable samples. The substrates, Apiezon M coated stainless foil, were weighted on a Perkin-Elmer microbalance to 0.01 mg. Each day four tests were conducted at the inlet and two parallel tests were conducted at the outlet of the precipitator. The rapping emissions were also conducted by sampling alternately with two separate pairs of impactors. One pair was used during rapping, and the other was used between rapping.

Supporting measurements included velocity traverse and Orsat measurements. Two ultrafine sampling systems were used, one at the inlet and the other at the outlet. Both systems contained an electrical aerosol analyzer and a Climet optical particle counter. The inlet system had three porous wall dilution stages. One was located in the stack; the other two stages, outside. The combined maximum dilution range was up to 2000 to 1. The outlet dilution system was a single porous wall diluter in the stack.

Charge-to-Mass Probe

The charge-to-mass of the particulate was measured at the inlet and outlet of the precipitator with a filter probe similar to that developed by Denver Research Institute. A standard 47 mm filter holder was insulated from the probe and placed in a Faraday cage. A curved inlet sampling nozzle was used to obtain isokinetic sampling. The charge collected by the filter holder was measured with an electrometer with a strip chart output.

Ash Resistivity

The ash resistivity was measured with an in-situ probe developed by Southern Research Institute using the procedures described by Smith et al.(2) In addition, ash samples were analyzed for chemical composition and the results used in a resistivity prediction program described by Bickelhaupt.(3)

Sulfur oxides were measured by the controlled condensation method described by Cheney and Homolya.(4) The condensate and impinger catches were analyzed with ion chromatography.

TEST RESULTS

Overview

A summary of the test results will be presented with emphasis on the size distribution results. The details of the study and the results of the special test work is summarized in the final report.(5) The overall results will be covered, first, with a discussion of the size distribution data and, finally, aspects of the electrostatic precipitator performance evaluation.

Overall Results

The overall test results are sumarized in Table 2. The tests were conducted with gas volumetric flow rates slightly higher than design. The efficiencies were consistent with previous tests at the site, and the emissions were within any applicable limitations. Of particular interest was the large emission of particles re-entrained during rapping. Often during the test, rapping puffs were visible from the stack.

Particle Size Distribution

The results of the size distribution measurements are shown in Figures 1a to 2b. The data are presented in the form of dM/dlogD as a function of particle diameter on semilogarithmic coordinates. The area under the curve is proportional to total mass concentration. Because of the wide range in concentrations, the cascade impactor data are plotted separately from the fine particle results. The distribution was bimodal, similar to that reported by Markowski et al.(6)

The rapping loss size dependence is shown in Figure 3. Over 80 percent of the emission was due to rapping re-entrainment. The cumulative distribution of the rapping puff is shown in Figure 4. The mean diameter and standard deviation are similar to that reported by Gooch and Marchant.(7)

Size Dependent Penetration

The particle size dependent penetration was computed by taking the ratio of outlet to inlet particle size distributions. The particle size dependent penetrations are shown in Figure 5. The measurements from cascade impactors and the fine particle measuring system are shown. It was noticed that a discrepancy existed between the impactors taken under rapping conditions and the ultrafine particle results. While good agreement existed for the nonrapping case. The rapping emissions were of sufficient concentration to cause unstable conditions even though an averaging volume was used. Thus, the stable in between rapping conditions were used in the fine particle results.

Electrical Conditions

Voltage-Current Curves

The voltage-current (V-I) curves were taken at the end of each day with the boiler and precipitator operating identically to the test condition. One section at a time was evaluated with the other sections energized. The V-I curves changed during the test with the operating currents increasing by 25 to 30 percent during the test. The change in the V-I characteristic is believed to be due to ash layer changes caused by the combustion of oil during a pulverizer malfunction midway through the test. The average operation power is presented in Table 3. The difference between the characteristics of Section 3 and the other sections. Hypothesis of plate alignment or heavy plate ash deposits are inadequate to explain the discrepancy.

Power Input

The power input was obtained from the secondary voltage and current and is reported in Table 3. The power was slightly lower on the low load cases than reported for conventional precipitators.

Resistivity

The resistivity was measured with an in-situ probe, reported by Smith et al.(2) and a computer prediction reported by Bickelhaupt(3). The results are summarized in Table 3 and Figure 5. The precipitator was operated at a temperature corresponding to the maximum on the curve.

The difference between the in-situ data and the prediction is believed to be due to the high carbon content of the ash. The SO_3 content was found not to be important in the determination.

Modeling

The model of the precipitator is described by Lawless et al.(8) and for that reason will not be described here. The geometry was approximated by a single wire instead of needles.

CONCLUSIONS

The precipitator was performing as designed, in compliance with applicable regulations. However, about 80 percent of the emissions measured resulted from plate rapping rather than direct penetration through the precipitator. In addition, the emissions were found to be very dependent on gas velocity.

ACKNOWLEDGMENT

This work was conducted as part of a Cooperative Agreement No. R-805897-03 with the U. S. Environmental Protection Agency. The cooperation of Mr. V. F. Wilkerson of the North Carolina Finishing Division of Fieldcrest Mills, Inc., and Dr. C. G. Noll of the United McGill Corporation is greatly appreciated.

ENDNOTES

1. Wilson, R., Jr., P. Cavanaugh, K. Cushing, W. Farthing, and W. Smith. Guildelines for Particulate Sampling in Gaseous Effluents from Industrial Process. U. S. Environmental Protection Agency. EPA-600/ -79-028, 1979.

2. Smith, W. B., K. M. Cushing, J. D. McCain. Procedures Manual for Electrostatic Precipitation Evaluation. U. S. Environmental Protection Agency. EPA-600/7-77-059.

3. Bickelhaupt, R. E. A Technique for Predicting Fly Ash Resistivity. U. S. Environmental Protection Agency. EPA-600/7-79-204, 1979.

4. Cheney, J. L., and J. B. Homolya. Sampling Parameters for Sulfate Measurement and Characterization. EST. 13:584-588, 1979.

5. Ensor, D. S., P. A. Lawless, A. S. Damle, A. D. Shendrikar, A. S. Viner, and E. R. Kashdan. Evaluation of the United McGill Electrostatic Precipitator. Report in preparation to EPA as part of Cooperative Agreement.

6. Markowski, G. R., D. S. Ensor, R. G. Hooper, and R. C. Carr. A Submicron Aerosol Mode in Flue Gas from a Pulverized Coal Utility Boiler. EST 14: 1400, 1980.

7. Gooch, J. P., and G. H. Marchant. Electrostatic Precipitator Rapping Re-Entrainment and Computer Model Studies. Electric Power Research Institute Report No. EPRI FP-792, 1978.

8. Lawless, P. A., J. W. Dunn, and L. E. Sparks. A Computer Model for ESP Performance. Presented at the EPA Third Symposium on the Transfer and Utilization of Particulate Control Technology, Orlando, Florida, March 9-12, 1981.

TABLE 1. DESIGN SPECIFICATIONS

Manufacturer	United McGill
Model	4-400 x 2 EP
Gas volume treated (both precipitators)	70.8 m^3/sec at 193°C (150,000 acfm at 380°F)
Plate area	8.070 m^2 (86,880 ft^2)
Plate height	3.05 m (10 ft)
Design SCA	108 m^2/m^3/sec (549 ft^2/k acfm)
Fields	4
Plate spacing	0.08 m (3.15 in.)
Plate thickness	
Collector	2.1 mm (0.082 in.)
Discharge	1.9 mm (0.075 in.)

TABLE 2. SUMMARY OF TEST RESULTS

Condition	Boiler $\left(\frac{\text{k lb steam}}{\text{hr}}\right)$	SCA $[m^2/(m^3/sec)]$	Inlet (mg/DNm^3)	Outlet (mg/DNm^3)	Penetration (percent)	Efficiency (percent)
High load	131	92	3970	383	9.65	90.4
Low load	126	100	3860	99.7	2.58	97.4
During rapping (high load)	132	96	2980	828	27.8	72.2
Between rapping (high load)	132	96	2980	18	0.6	99.4

Design SCA = 108 $m^2/(m^3/sec)$

TABLE 3. OPERATING CONDITIONS

Resistivity			
Measured		1×10^{13} Ω-cm	
Predicted from ash composition		2×10^{12} Ω-cm	
Power			
93 - 122 w/(acfm/1000)			
Secondary Voltage and Current:*		Voltage (kV)	Current (ma)
1		30	27
2		23.2	70
3		20	112
4		24.5	110
Sulfuric Acid	12 ppm		
Sulfur Dioxide	1430 ppm		
Excess Oxygen	9%		
Average Opacity	2-7%		

* Low load conditions.

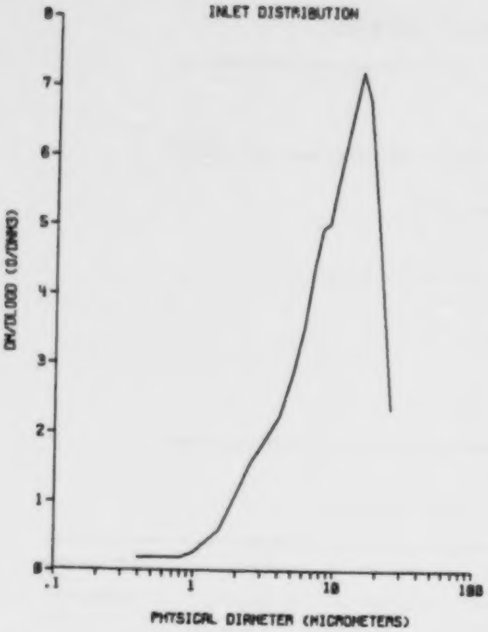


Figure 1a. Inlet particle size distribution determined by cascade impactor.

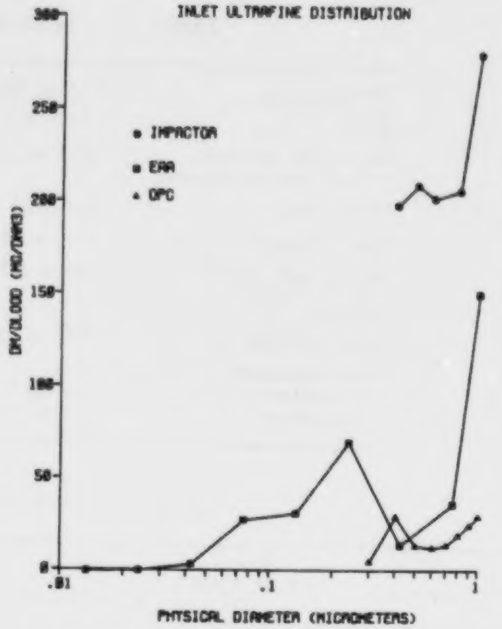


Figure 1b. Inlet particle size distribution determined by ultrafine sampling system.

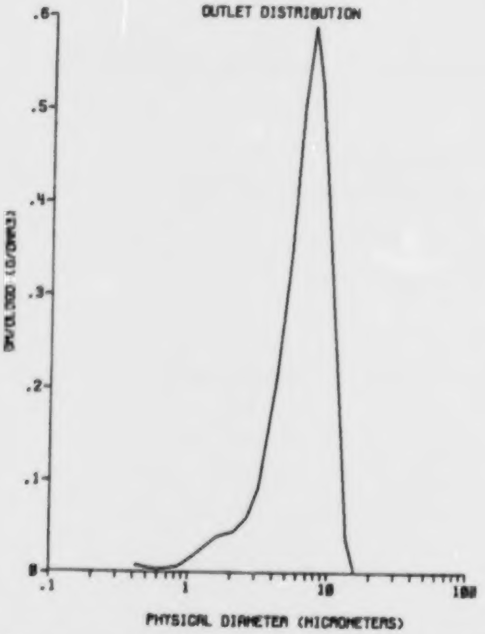


Figure 2a. Outlet particle size distribution determined by cascade impactor.

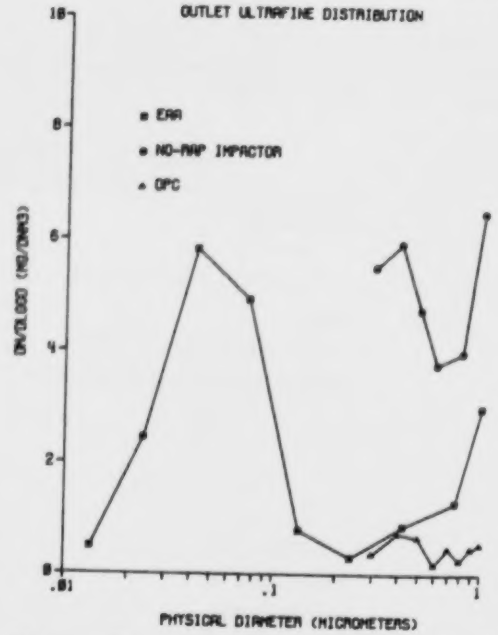


Figure 2b. Outlet particle size distribution determined by ultrafine sampling system.

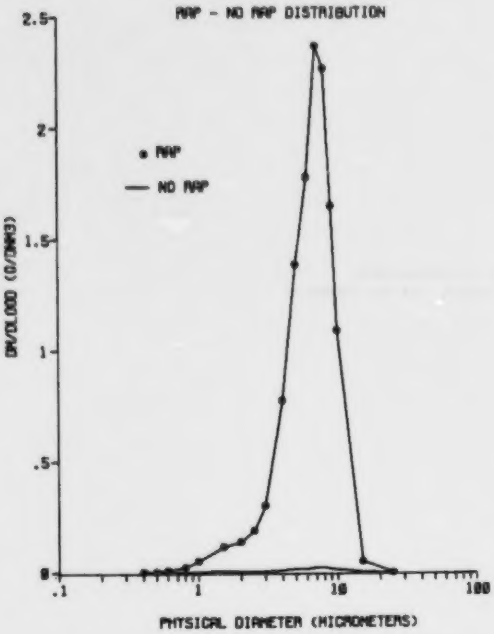


Figure 3. Comparison of rapping emission between rapping.

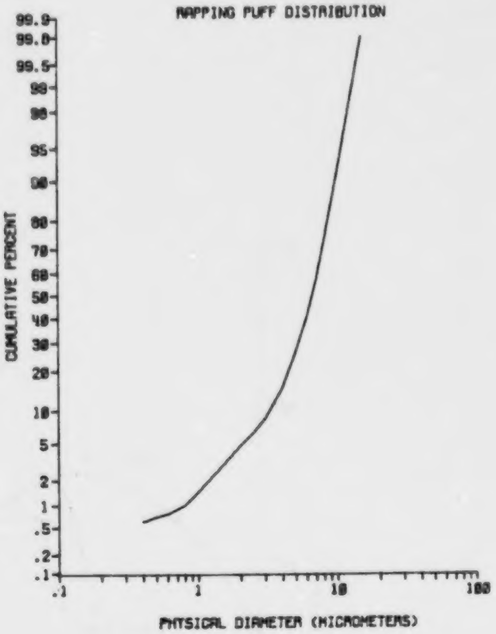


Figure 4. Cumulative particle size distribution of the rapping puff.

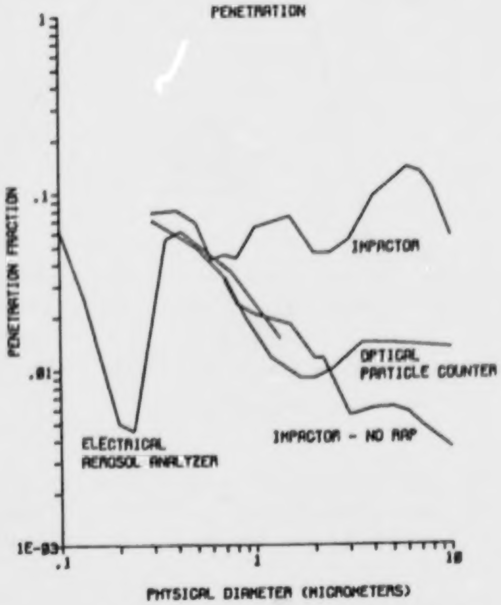


Figure 5. Particle size dependent penetration through the baghouse.

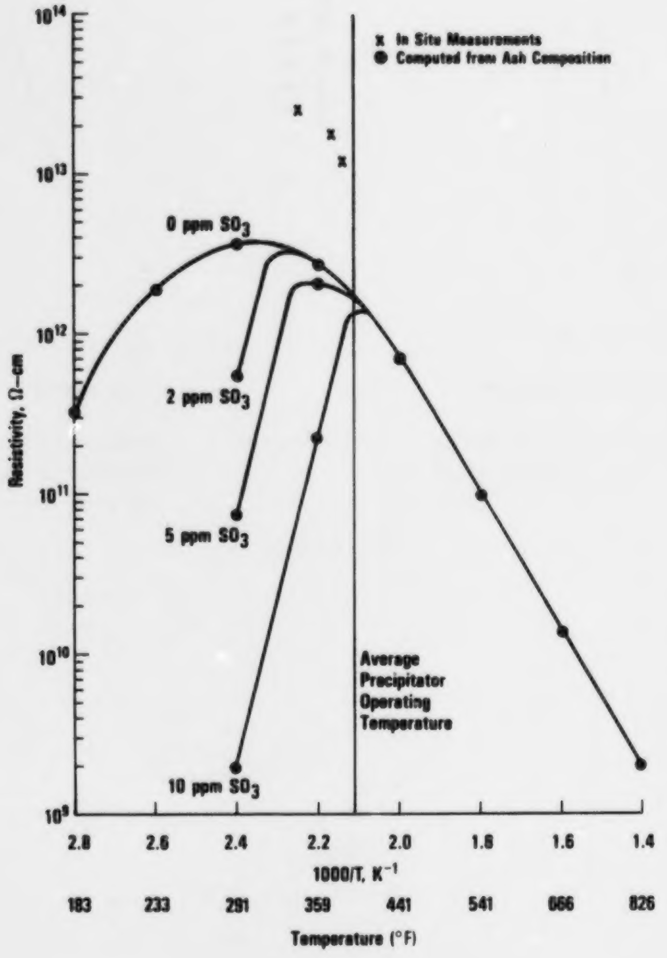


Figure 6. Particle resistivity from in-situ measurement and prediction from composition following Bickelhaupt(3).

PREDICTING THE EFFECT OF PROPRIETARY CONDITIONING AGENTS ON FLY ASH RESISTIVITY

Raymond J. Jaworowski, Technical Director, International Operations
John J. Lavin, Associate Director, Applications Engineering

Apollo Technologies Inc.
One Apollo Drive
Whippany, New Jersey 07981

ABSTRACT

Fly ash resistivity plays an important role in the performance of electrostatic precipitators. As ash resistivities approach approximately 5×10^{10} ohm-cm, operational problems occur.

Recognition of flue gas conditioning agents as a means to lower ash resistivity has placed increased emphasis on the development of predictive methods to determine how the resistivity will be influenced by a specific chemical.

Based on previous work by Bickelhaupt and Sparks, a correlation has been developed to predict the effects of proprietary chemicals on fly ash resistivity. The correlation is relatively insensitive to temperature, field strength, and coal type.

Data from field trials are used to demonstrate the effectiveness of this approach. Excellent agreement between predicted and measured results has been obtained.

INTRODUCTION

Fly ash resistivity plays a significant role in the design of electrostatic precipitators. As fly ash resistivities approach and exceed approximately 5×10^{10} ohm-cm, operational problems occur. Many of these problems can be controlled in the specification stage, by changing various parameters in the precipitator design such as collecting area, residence time, precipitator power, and the use of "hot side" precipitators. However, when a precipitator already exists it is virtually impossible to change most of these parameters, with the possible exception of additional power. In the case where resistivity problems impair performance or when a projected shift in coal supply might result in a resistivity problem it becomes important to be able to measure or predict the resistivity of the fly ash as it exits the boiler.

With problem resistivities it is equally important to be able to predict if a significant reduction in resistivity can be accomplished through the use of chemical conditioning agents. This information can then be used to determine the degree of improvement in precipitator performance to be expected through the use of fly ash conditioning.(1)

A significant volume of work exists describing relationships between fly ash resistivity and various other parameters, including chemical composition, flue gas temperature, dew point, etc. (2,3,4,5) Recently Bickelhaupt and Sparks (6) published a comprehensive technique for predicting fly ash resistivity, which is based on Bickelhaupt's previous work on calculating bulk resistivity from fly ash elemental analysis. This report includes a computer program to calculate bulk resistivity and then allows adjustments for flue gas moisture concentration, applied electrical stress, and sulfur trioxide (SO_3) content in the flue gas. Development of the SO_3/resistivity relationship involved modifying the ASTM bulk resistivity probe (7) to allow measurement of a 1-mm ash layer after an equilibration time of 16-18 hours. This process was then extrapolated to estimate the effect on resistivity of additional SO_3 conditioning.

In view of the importance of resistivity modification to the utility industry, a study was undertaken to correlate data obtained from actual field trials with the existing Bickelhaupt and Sparks program, to determine if a procedure to predict the effect of proprietary flue gas conditioning agents on fly ash resistivity could be developed. This report describes the results of this investigation.

BICKELHAUPT/SPARKS CALCULATIONS

Bickelhaupt and Sparks have developed an expression to calculate the basic (bulk) resistivity as a function of ash composition. This equation was then modified to include expressions for temperature, moisture, sulfur trioxide concentration, and the ash layer field strength. The results have been incorporated into a computer program which is part of the published paper. The input data required and output from the program are shown in Table I. While complete ultimate and ash analyses are desirable, the program actually requires knowledge of only moisture and sulfur dioxide (SO_2) concentrations in the flue gas and atomic concentrations of lithium, sodium, magnesium, calcium, and iron. The program makes a few assumptions, such as flue gas composition is based on 30% excess air, the SO_3 concentration is 0.4% of the SO_2 level in the flue gas, and that the ash resistivity is measured at a field strength of 10 kilovolts per cm. Based on these assumptions, the output data can be plotted as shown in Figure 1 to yield a typical temperature resistivity curve. Field tests at six power stations comparing the predicted resistivity with actual in situ measurements showed good correlation.

CORRELATION OF APOLLO FIELD DATA

Five flue gas conditioning trials were selected where sufficient information had been obtained to use in a correlation analysis. Table II lists the pertinent boiler, precipitator, flue gas, and fly ash information for each station. Table III lists the chemical additive type and feed rate, the resulting measured baseline (untreated) and treated resistivities, and the calculated baseline resistivities. Actual moisture and SO_2 concentrations were used to calculate baseline predicted resistivity values, as ultimate coal analyses were not performed during these early trials. Field resistivities were obtained in situ using a probe of the SRI design.

The effect of resistivity modifiers can be calculated using the expression for the sum of parallel resistances (Equation 1) stated in terms of resistivity if the correlation factor is known.

$$\rho t = \frac{\rho b \times \rho c}{\rho b + \rho c} \qquad (1)$$

where: ρ_t = treated (final) resistivity
ρ_b = baseline (untreated) resistivity
ρ_c = surface resistivity resulting from adsorption of additive (correlation factor)

Rearranging Equation 1 to allow direct calculation of the additive surface resistivity component yields the expression shown in Equation 2:

$$\rho_c = \frac{\rho_b \times \rho_t}{\rho_b - \rho_t} \qquad (2)$$

The additive surface resistivity values then were calculated using the measured baseline and treated resistivity values, and are also listed in Table III. A plot of these results vs. additive concentration is shown in Figure 2. A correlation coefficient of 0.901 was obtained from the 11 data points.

These results were very encouraging and further examination of the field data indicated the following conclusions:

A. Field resistivity measurements were insensitive to the field strength used in the in situ resistivity probe.

B. Temperature effects were minimal. This is due to the fact that the additives have extremely low vapor pressures as compared to SO_3 over the temperature range evaluated.

C. Additive performance response did not appear to be directly related to coal type. The resulting equation fit Bickelhaupt's classification for eastern and western coals, as well as Texas Lignite.

FIELD TRIAL RESULTS

Three different sites were chosen to evaluate the ability to predict resistivity modification through the use of the correlation factor just developed. Table IV lists the pertinent boiler, precipitator, and fly ash information for these trials. Flue gas analysis (percent moisture, ppm_v SO_2) was used in the program rather than the ultimate coal analysis to calculate the flue gas chemistry, and the field strength was assumed to be 10 KV/cm. In all cases the baseline resistivity was calculated using the Bickelhaupt/Sparks equation, and that result was used to calculate treated resistivities using the correlation factor shown in Figure 2. The additive shown had been selected for use at the stations based on previous evaluations. These results are shown in Table V.

Field measurements of resistivity were then made for both the untreated (baseline) and treated cases. In addition, a second set of resistivity calculations was made for the treated case using the measured baseline resistivity. All of these results are shown in Table V. At two of the three stations (Ma and BB) excellent agreement was obtained between the calculated and measured resistivities for both the treated and untreated cases. In addition, the calculated resistivities from the measured baseline were also in excellent agreement with the measured treated readings. These results show that in most cases chemical additive performance can be predicted from either a calculated or measured baseline resistivity level. The agreement obtained between calculated and measured results is well within the experimental reproducibility normally associated with in situ field resistivity measurements.

At station "FC" (Table V) as well as at station "A" (Table III) the predicted resistivities were significantly lower than those measured during the field trials. The reasons for this are not fully understood at this time, but it is possible that errors in coal analysis due to nonhomogeneity of the coal supply may have occurred. A second possibility is that the higher ratio of sodium, potassium, and iron to calcium and magnesium in these two cases may bias the computer calculation. Additional data is currently being examined to determine if this inconsistency is real.

PRECIPITATOR PERFORMANCE

A significant improvement in precipitator performance was found with the use of additives at all the stations in this study, both those for the correlation development and for the final field trials. In many cases, improvements were greater than those expected through theoretical considerations. (1) The field data is currently being reviewed to determine the contribution to performance improvement by both resistivity changes and other factors such as reentrainment, space charge modification, etc. This information will be reported as soon as the investigation is complete, but some preliminary results are listed in Table VI.

CONCLUSION

The Bickelhaupt/Sparks equation is a useful tool for predicting resistivity from fly ash chemistry. By extending this equation, it is now possible to predict the effect of proprietary chemical additives on fly ash resistivity. The developed correlation has been tested in three field trials with excellent results. In addition to demonstrating resistivity predictability, significant relationships between electrostatic precipitator performance and resistivity have been observed. These relationships are being fully evaluated and will be reported in a subsequent work.

ENDNOTES

1. Sparks, L. E., SR-52 Programmable Calculator Programs for Venturi Scrubbers and Electrostatic Precipitators, EPA-600/7-78-026, 1978.

2. Wagoner, C. L., et al, Fuel and Ash Evaluation to Predict Electrostatic Precipitator Performance. Presented at the ASME/IEEE Joint Power Generation Conference, Long Beach, Calif., Sept. 18-21, 1977.

3. Bickelhaupt, R. E., Influence of Fly Ash Compositional Factors on Electrical Volume Resistivity, EPA-650/2-74-074, 1974.

4. Bickelhaupt, R. E., Effect of Chemical Composition on Surface Resistivity of Fly Ash, EPA-600/2-75-017, 1975.

5. Maartmann, Sten, The Effect of Gas Temperature and Dew Point on Dust Resistivity and thus the Collecting Efficiency of Electrostatic Precipitators, Second International Clean Air Congress of the International Union of Air Pollution Prevention Association, Washington, D.C., 1970.

6. Bickelhaupt, R. E. and Sparks, L. E., A Technique for Predicting Fly Ash Resistivity, EPA 600/7-79-204, 1979.

7. American Society of Mechanical Engineers, Power Test Code 28, Determining the Properties of Fine Particulate Matter; Section 4.05, Method for Determination of Bulk Electrical Resistivity, 1965.

TABLE I: PROGRAM DATA INPUT AND OUTPUT[6]

	Data Input		Used by Program
1.	Ultimate Coal Analysis (%) C, H_2, O_2, N_2, S, H_2O, ash	1.	Flue Gas Composition % H_2O, ppm_v SO_2
2.	Coal Ash Analysis (%) Li_2O, Na_2O, K_2O, MgO, CaO, Fe_2O_3, Al_2O_3, SiO_2, TiO_2, P_2O_5, SO_3	2.	Atomic % Li + Na, Mg + Ca, Fe
3.	Field Strength (KV/cm) Actual or 10	3.	Same

Typical Program Output

TEMP 1000/T(K)	DEG K	DEG C	DEG F	RHO (VS)	RHO(VSA)
1.4	714	441	826	2.2E+09	2.2E+09
1.6	625	352	666	1.6E+10	1.6E+10
1.8	556	283	541	1.1E+11	1.1E+11
2.0	500	227	441	6.3E+11	3.9E+11
2.2	455	182	359	1.2E+12	7.1E+10
2.4	417	144	291	7.3E+11	5.5E+09
2.6	385	112	233	2.6E+11	-
2.8	357	84	183	2.1E+10	-

where: RHO(VS) = Resistivity excluding SO_3 effect

RHO(VSA) = Resistivity including SO_3 effect

TABLE II: BOILER AND FLY ASH DATA FOR CORRELATION

Station:	C	G	Mo	A	B
Load (Mw):	350	100	575	146	700
Boiler Manufacturer:	C.E.	C.E.	C.E.	C.E.	C.E.
ESP SCA (ft^2/1000 acfm):	135	209	186	352	145
ESP Temperature (^oF):	250	360	380	350	275
Firing Method:	P.C.	P.C.	P.C.	P.C.	P.C.
Coal Type:	Western	Western	Lignite	Eastern	Eastern
Proximate Coal Analysis					
Ash (%):	6	5-8	13.5	13.5	13.8
Sulfur (%):	0.5	0.6	0.5	1.7	1.5
Moisture (%):	12	6.5	31	3.7	6.5
Flue Gas Analysis					
Moisture (%):	6	7	15.5	7	8
SO_2 (ppm_v):	370	500	490	1250	800
Elemental Coal Analysis*					
SiO_2 (%):	64.68	54.7	55.92	52.4	50.82
Al_2O_3(%):	22.23	18.5	26.02	29.8	24.07
Fe_2O_3 (%):	3.37	8.9	4.30	11.6	19.21
MgO (%):	0.40	0.8	2.58	0.1	0.52
CaO (%):	7.34	16.7	10.32	2.3	1.45
Na_2O (%):	0.69	0.5	0.11	4.9	0.62
K_2O (%):	1.29	0.8	0.75	2.7	3.31
Li_2O (%):	**	**	**	0.1	**

*Corrected to 100% total.
**Not analyzed; assumed less than 0.1%.

TABLE III: CHEMICAL ADDITIVES AND RESISTIVITY DATA FOR CORRELATION

		Treatment Rate		Measured Fly Ash Resistivity	Surface Resistivity Factor
Station	Additive	(GPT)	(ppm_v)	(10^{11} ohm-cm)	(10^{11} ohm-cm)
C	LPA-40	0	0	6.9 (3.0)*	-
		0.10	3.2	3.0	5.3
		0.15	4.7	1.7	2.3
	LPA-410M	0.15	2.4	2.4	3.7
		0.30	4.8	1.5	1.9
		0.40	6.3	0.9	1.1
		0.50	7.9	0.7	0.8
G	LPA-40	0	0	5.1 (3.5)*	-
		0.20	6.9	0.8	0.95
Mo	LPA-410	0	0	3.5 (5.8)*	-
		0.15	9	0.5	0.6
		0.20	12	0.2	0.2
A	LPA-40	0	0	10.0 (0.03)*	-
		0.15	4.4	3.5	5.4
B	LPA-40	0	0	1.0 (2.4)*	-
		0.15	5.1	0.40	0.7

*Calculated Baseline Resistivities from Bickelhaupt/Sparks Program

GPT = Gallons of Additive per Ton of Coal Fired

TABLE IV: BOILER AND ASH DATA FROM FIELD TRIALS

Station:	Ma	BB	FC
Load (Mw):	400	575	800
Boiler Manufacturer:	C.E.	C.E.	B&W
ESP S.C.A. (ft^2/1000 acfm):	175	156	165
ESP Temperature (^oF)	280	370	225
Firing Method:	P.C.	P.C.	P.C.
Coal Type:	Eastern	Lignite	Western
Proximate Coal Analysis			
Ash (%):	16.4	14	23
Sulfur (%):	1.5	0.75	0.8
Moisture (%):	1.1	24	4.3
Flue Gas Analysis			
Moisture (%):	7	13	9
SO_2 (ppm_v):	8000	1000	750
Elemental Coal Analysis*			
SiO_2 (%):	64.2	62.0	58.91
Al_2O_3 (%):	26.4	17.4	28.11
Fe_2O_3 (%):	5.7	6.6	4.72
MgO (%):	0.1	1.5	0.64
CaO (%):	1.0	13.3	3.97
Na_2O (%):	0.7	1.1	2.04
K_2O (%):	3.5	1.2	1.61
Li_2O (%):	**	**	**

*Corrected to 100% total.

**Not analyzed; assumed less than 0.1%.

TABLE V: RESISTIVITY RESULTS

Station	Additive	Treatment Rate (GPM)	Treatment Rate (ppm$_v$)	Fly Ash Resistivity (10^{11} ohm-cm) Calculated*	Fly Ash Resistivity (10^{11} ohm-cm) Measured	Fly Ash Resistivity (10^{11} ohm-cm) Calculated**
Ma	LPA-410M	0	0	3.0	1.3	-
		0.10	4.1	1.4	0.81	0.89
		0.20	8.2	0.54	0.34	0.44
BB	LPA-410	0	0	2.0	3.0	-
		0.20	9	0.4	0.4	0.42
FC	LPA-40	0	0	0.33	3.9	-
		0.10	3.7	0.21	2.3	1.7

*From calculated baseline
**From measured baseline

TABLE VI: MEASURED PRECIPITATOR PERFORMANCE

Station	Additive	Treatment Rate (GPT)	Predicted Efficiency (%)	Measured Efficiency (%)
A	LPA-40	0	94.9	92.2
		0.15	94.9	99.7
Ma	LPA-410M	0	92.0	91.5
		0.20	97.4	98.6
BB	LPA-410	0	85.3	95.9
		0.20	95.1	99.3

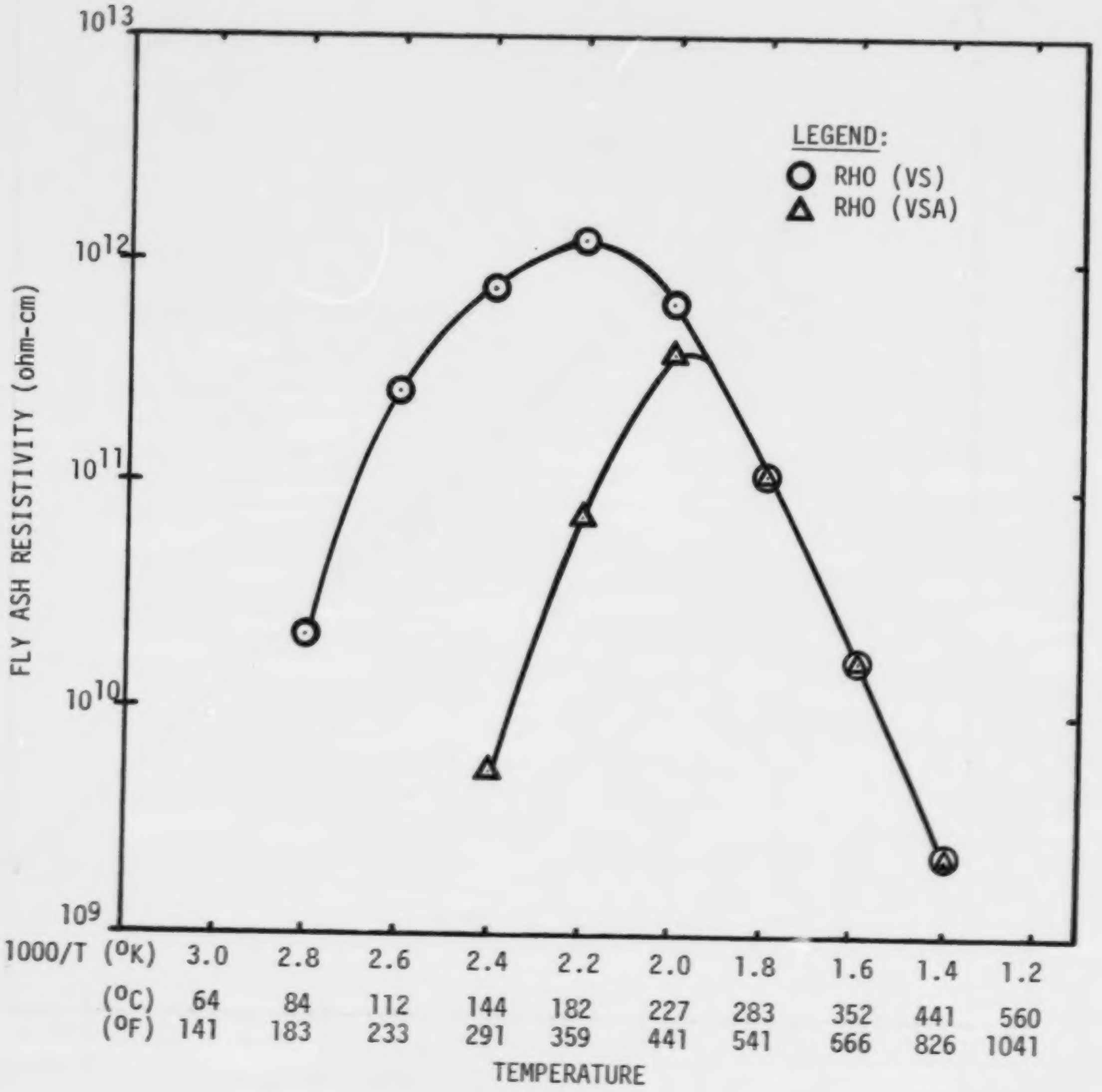


FIGURE 1 - PREDICTED RESISTIVITY FOR THE COAL AND ASH USED TO ILLUSTRATE THE COMPUTER PROGRAM(6)

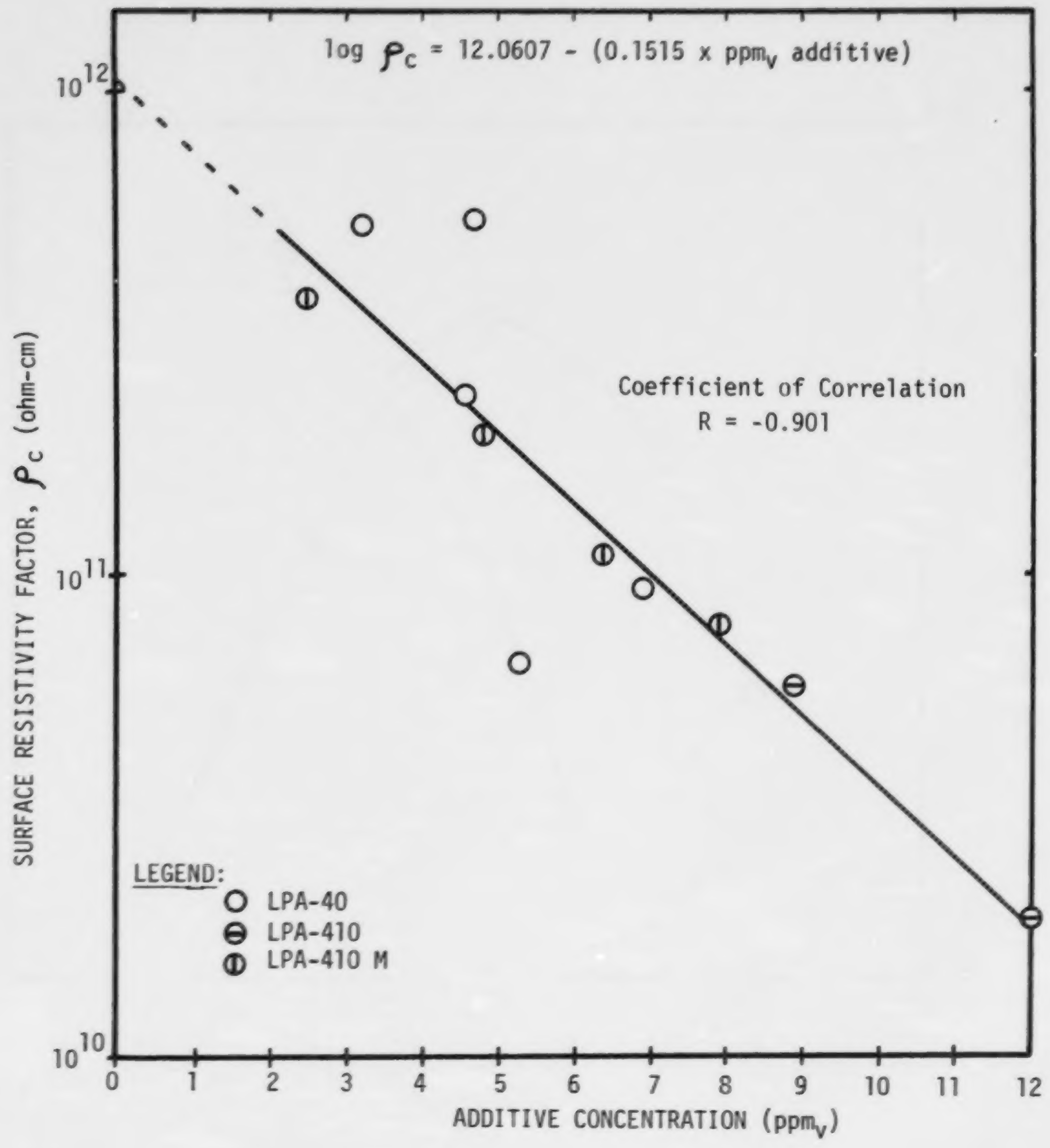


FIGURE 2 - EFFECT OF ADDITIVE ON SURFACE RESISTIVITY FACTOR

SO_3 CONDITIONING TO ENABLE ELECTROSTATIC PRECIPITATORS TO MEET DESIGN EFFICIENCIES

BY:

J. J. FERRIGAN III
WAHLCO, INC.
SANTA ANA, CALIFORNIA 29704

This is a case study involving a particular utility's and precipitator manufacturer's problem of selecting an effective and reliable method of increasing the collection efficiencies of two new electrostatic precipitators to their design specifications. This paper traces the study from the time of erection of the two cold-side precipitators in the early 1970's to the final solution which was SO_3 flue gas conditioning in 1979.

We detail the mechanical modifications and consultant's recommendations which were undertaken to no avail. We point out that after all possible mechanical fix-ups had been completed, proprietary chemical conditioning of the flue gas was tried, which proved to be more detrimental than good. Finally, SO_3 flue gas conditioning was tried, and it brought both cold-side precipitators into design compliance. These facts are supported by precipitator outlet grain loading tests, which show that SO_3 flue gas conditioning enabled the precipitators to operate under the .02 gr/scf limit.

INTRODUCTION

This is a case study concerning two cold-side electrostatic precipitators designed to collect fly ash generated from the burning of low sulfur Eastern Bituminous Coal. (See Table 1). The two electrostatic precipitators referred to as "A" and "B", were erected in 1973 and designed to accommodate a flue gas volume of 110,000 ACFM each. The total specific collecting area (SCA) for each precipitator is 600+. The first three fields have transformer-rectifiers rated at 700 MA and the last four fields are rated at 1000 MA. The two "NEW" electrostatic precipitators are preceded by two "OLD" electrostatic precipitators which had been in operation for twenty years (See Figure 1). The two "NEW" electrostatic precipitators were designed to operate at 99.8% efficiency with the "OLD" precipitators off line.

In the first quarter of 1975 the precipitator manufacturer conducted the first acceptance tests on "A" precipitator. (See Table 2). These results indicated that there was trouble ahead. The migration velocities were extremely low with an average of 2.54 cm/sec. The outlet grain loading was a factor of ten away from the design outlet grain loading option of 0.02 gr/scf. The power levels of the precipitators were also extremely low. The highest reading obtainable on all seven T/R sets was 100 MA on the last field. These results pointed to a variety of possible problems.

SOLUTIONS

The utility and precipitator manufacturer spent the next two years investigating the problems with "A" and "B" precipitators. They tried several methods of increasing the efficiency of the precipitators. Listed below are the actions that were taken to increase the efficiency and the results of these actions.

1. Power off rapping was initiated by the precipitator manufacturer which resulted in no improvement of precipitator efficiency.

2. Saddle weights were added to the existing wire weights to reduce slack in the discharge electrodes. This step was initiated by the precipitator manufacturer with no improvement of precipitator efficiency.

3. Flail hammer rappers were installed to measure the effectiveness of this form of rapping versus the low frequency magnetic impulse rappers. This program was initiated by the precipitator manufacturer with no improvement of precipitator efficiency.

4. Lowering of the air heater outlet temperature to reduce the resistivity of the fly ash was attempted. This step was initiated by the utility and resulted in no improvement of precipitator efficiency.

5. An independent consultant was retained to determine why the precipitator would not perform when low sulfur coal was being fired in the boilers. The consultant's final conclusion was that further rapping improvement efforts should be initiated. He also stated that the gas distribution was acceptable.

6. A second consultant was retained. His conclusions were that the gas distribution was poor and the subject precipitators should be fully optimized by including a new rapping system, correcting gas distribution and adding transformer-rectifiers. He also stated that gas conditioning, utilizing some form of sulfur oxide input into the gas stream, would be quite effective in lowering resistivity and increasing the efficiency of the precipitators.

7. Finally the precipitator manufacturer considered the use of flue gas conditioning as a possible solution and decided to pursue proprietary chemical additives as the method.

PROPRIETARY CHEMICAL GAS CONDITIONING

The proprietary chemical gas conditioning system was selected over SO_3 flue gas conditioning solely due to capital cost. The total capital cost for the proprietary chemical gas conditioning system was approximately $60,000.00 versus $180,000.00 for the SO_3 flue gas conditioning system.

The proprietary chemical gas conditioning system chosen is a process which involves injecting a liquid additive conditioning agent upstream of the air preheater to reduce the resistivity of the fly ash. The chemical is injected upstream of the air preheater to allow for vaporization of the conditioning agent. The chemical constituents of the additive would not be divulged by the manufacturer. The initial injection rate of the conditioning agent was 0.1 gal/ton of coal which was eventually raised to 0.3 gal/ton. This conditioning agent had no effect on either the stack opacity or the power in the subject precipitator. Eventually, their chemical caused pluggage of the air preheater (5" pressure drop across the air preheaters). The utility had the chemical analyzed and found it to be ammonium sulfate, $(NH_4)_2SO_4$ and 60% H_2O.

After failing with the ammonium sulfate, the utility was approached by the precipitator manufacturer and asked their permission to inject a new chemical. The utility had this new chemical analyzed and found it to be Sodium Bisulfate ($NaHSO_4$) and 60% H_2O. This chemical was very acidic ($PH<1$) and was very corrosive and difficult to handle. The utility allowed this new conditioning agent to be tried for a thirty-day period. (See Table 3). The initial injection rate of this conditioning agent was 0.1 gal/ton and eventually was raised to 0.5 gal/ton with no effect on the outlet grain loading. The emission rate was not within a factor of ten of meeting the outlet option for contract design guarantee which was 0.02 gr/scf. In addition, after only one week of injection of the chemical, the 304-stainless steel atomizer tip on the injection nozzle was completely corroded away.

Another major disadvantage of the proprietary chemical conditioning system was the operating cost. The operating cost for injecting 0.3 gal/ton of this chemical into each boiler "A" and "B" was approximately $18,000.00/month.

Needless to say the utility's view of flue gas conditioning was not very optimistic after this episode, but nevertheless SO_3 flue gas conditioning had to be considered the only other viable solution to the existing problems with the subject precipitators.

SO_3 FLUE GAS CONDITIONING

From correspondence with other major utilities it was discovered that they were using, quite successfully, SO_3 flue gas conditioning to help maintain particulate collection efficiency and opacity requirements. After consulting these electric utilities, field trips were conducted to observe the systems in operation. The major point that was made clear by the other operating utilities was that SO_3 injection would allow the precipitators to perform as well as they would with high sulfur coal.

The utility had very good results when burning high sulfur coal in boiler "A". One specific group of tests conducted in 1974, by the utility, with coal that had an average sulfur content of 3.94% and an average ash content of 20.75%, yielded an outlet grain loading of 0.011 gr/scf for precipitator "A". Based on this and other data, it was decided that the precipitator manufacturer should pursue SO_3 flue gas conditioning as a final solution.

The precipitator manufacturer purchased SO_3 flue gas conditioning equipment to condition the fly ash going to both "A" and "B" precipitators. This was an SO_2 source system consisting of a liquid SO_2 storage tank, liquid SO_2 vaporizer, air filters, fans, SCR controlled air heaters, SO_2/SO_3 catalytic converters and injection probes. Process instrumentation provided failsafe operation and automatic adjustment of SO_3 production in response to boiler load. The system was designed to inject 40 PPM of SO_3 into both flue gas streams of 110,000 ACFM at 300°F.

TEST RESULTS WITH SO_3 FLUE GAS CONDITIONING

In October 1979, the SO_3 flue gas conditioning system was installed and operational. The same quality low sulfur coal was being fired as when the proprietary chemical gas conditioning system was being tested. The utility had agreed that the outlet option of 0.02 gr/scf would be sufficient in lieu of a precipitator efficiency test. Initially there was a seven-day optimization period while injecting SO_3 prior to testing. Improved electrical readings were observed during this time. (See Table 5). After this waiting period, outlet grain loading tests were conducted on "A" precipitator. The first three tests surpassed the guarantee, averaging 0.0157 gr/scf. (See Table 4). After these tests were completed "B" precipitator was tested and also surpassed the 0.02 gr/scf limit.

Not only did the SO_3 flue gas conditioning system enable the precipitator to meet design specifications, it also allowed the utility to support and maintain a system with a low operating cost. Based on an injection rate of 20 PPM, the total operating cost for both Units "A" and "B" was only $2,400/month.

CONCLUSION

The final decision to install an SO_3 flue gas conditioning system was a mutual agreement reached by both the precipitator manufacturer and the utility. Thousands of dollars could have been saved if high resistivity had been recognized initially as the problem with "A" and "B" precipitators. Tests conducted in 1974 proved that the burning of high sulfur coal enabled the precipitators to meet design specifications.

Hopefully this case study will enable precipitator manufacturers and the electric utilities to apply this information to the design of cold-side electrostatic precipitators in the future. The feeling for many years was that if you make them big enough they will work. This is not always true as shown in this case. After evaluating all possible solutions, one must agree that SO_3 flue gas conditioning is a reliable and cost efficient method in enabling cold-side electrostatic precipitators to meet federal particulate emission standards while collecting low sulfur coal fly ash.

Table 1 DESIGN SPECIFICATIONS FOR ELECTROSTATIC PRECIPITATORS "A" & "B"

Process	....	Steam Generation
Suspended Material	....	Fly Ash and Fume
Fuel	....	Coal (Eastern Bituminous)
Gas Source	....	Boilers (Steam Generators A & B)
Gas Volume	....	110,000 ACFM (Each)
Gas Temperature	....	325 to 350°F
Gas Moisture	....	4 to 5% By Weight as Fired
Pressure	....	Negative
Fuel Specifications:		
Ash	....	25%
Sulfur	....	1%
Guaranteed Efficiency	....	99.8%
Outlet Option	....	0.02 Gr/SCF
Surface Collecting Area	....	600+ SCA (Each)

Table 3 PRECIPITATOR TEST RESULTS USING PROPRIETARY CHEMICAL CONDITIONING ON PRECIPITATOR "A" (1978) (TESTS CONDUCTED BY INDEPENDENT CONSULTANT)

TEST NO.	DATE	STEAM FLOW (10^3 LBS/HR)	O_2 (%)	PROPRIETARY CHEMICAL (GPT)	EMISSION RATE (GR/SCF)
1	8/10	180	3.5	0.1	0.33
2	8/10	182	3.5	0.1	0.31
3	8/10	185	3.7	0.1	0.39
4	8/11	181	3.6	0.1	0.33
5	8/11	185	3.8	0.1	0.34
6	8/14	162	3.2	0.1	0.31
7	8/14	171	3.7	0.1	0.28
8	8/15	171	3.4	0	0.32
9	8/15	170	3.5	0	0.27
10	8/15	174	3.4	0	0.31
11	8/16	176	3.4	0.1	0.33
12	8/16	182	3.5	0.1	0.25
13	8/16	180	3.3	0.1	0.31
14	8/17	178	3.6	0	0.38
15	8/17	179	3.6	0	0.37
16	8/17	180	3.8	0	0.36
17	8/18	183	3.8	0.2	0.40
18	8/18	185	3.8	0.3	0.28
19	8/18	187	3.7	0.3	0.27
20	8/21	175	3.7	0.4	0.40
21	8/21	177	3.7	0.4	0.27
22	8/21	178	4.0	0.4	0.35
23	8/22	163	3.1	0.5	0.18
24	8/22	172	3.8	0.4	0.26
25	8/23	168	3.7	0.5	0.24
26	8/23	166	3.8	0.5	0.24
27	8/23	173	3.1	0.5	0.27
28	8/24	161	3.7	0.5	0.29
29	8/24	166	3.6	0.5	0.28
30	8/24	166	3.6	0.5	0.25

Note: Outlet Option for Contract Design Guarantee was 0.02 Gr/SCF

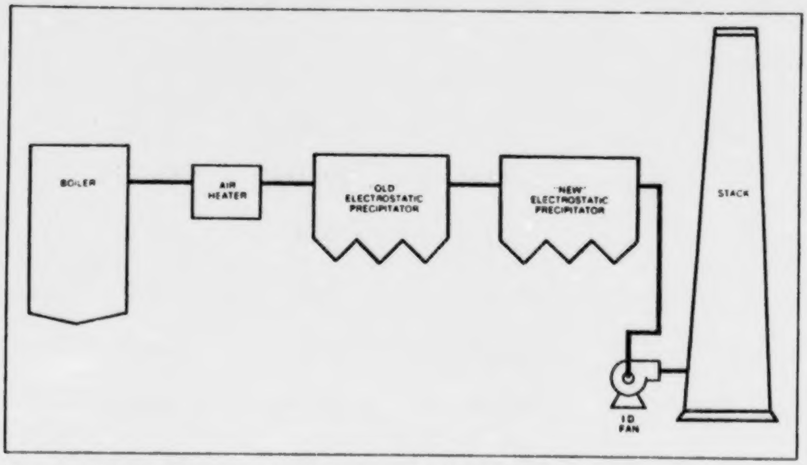

BOILER
AIR HEATER
OLD ELECTROSTATIC PRECIPITATOR
"NEW" ELECTROSTATIC PRECIPITATOR
STACK
I D FAN

Figure 1. Typical Schematic of Gas Flow For Units "A" & "B"

TABLE 2

Precipitator "A" Test Results, Acceptance Tests (1975) Without SO_3 Conditioning
(Tests Conducted by Precipitator Manufacturer)

Test No.	Inlet Loading (Gr/SCF)	Outlet Loading (Gr/SCF)	ω CM/SEC	Efficiency (%)	Gas Volume (ACFM @ Outlet)	Temperature (°F Outlet)
1	2.85	0.212	2.199	92.56	125,100	288
2	5.05	0.277	2.450	94.51	97,000	276
3	5.20	0.269	2.507	94.83	97,700	275
4	4.52	0.250	2.531	94.47	107,600	279
5	4.67	0.186	2.728	96.02	98,800	287
6	4.39	--	--	--	--	--
7	--	0.216	2.549	95.08*	97,900	277
8	3.84	0.173	2.622	95.49	90,600	267
9	4.88	0.231	2.583	95.27	91,800	270
10	4.82	0.225	2.593	95.33	99,100	268
11	4.97	0.171	2.636	95.56	96,400	276

*Based on Test 6 Inlet, Test 7 Outlet, Standard Conditions 70°F, 29.92" Hg.

Note: Guaranteed Design Efficiency was 99.8%.
Note: Tests 1 And 8 Were Recorded With The Old "A" Precipitator On Line.

Typical Coal Analysis
Proximate Analysis as Received

Moisture, %	3.45
Heating Value, BTU/Lb	10,698
Ash, %	23.13
Sulfur, %	1.04

Table 4 PRECIPITATOR TEST RESULTS USING SO_3 CONDITIONING ON PRECIPITATOR "A" (1979)
(TESTS CONDUCTED BY PRECIPITATOR MANUFACTURER)

TEST NO.	1	2	3
Location	Outlet	Outlet	Outlet
% Moisture	5.7	5.2	7.2
% Oxygen	5.0	5.0	5.0
% CO_2	14.5	14.5	14.5
Gas Temperature (°F)	300°F	300°F	300°F
Gas Volume (ACFM)	85,710	85,621	85,981
Emission Rate (Lbs/MMBTU)	0.0147	0.0112	0.0117
Gr/SCF	0.0186	0.0140	0.0145

Note: Outlet Option for Contract Design Guarantee was 0.02 Gr/SCF

Note:

1.	Average Outlet Grain Loading from New "A" Precipitator with SO_3 Conditioning	0.0157 Gr/SCF
2.	Average Inlet Grain Loading into New "A" Precipitator with Old "A" Off	4.81 Gr/SCF
3.	Estimated Efficiency Based on Inlet Assumptions	99.9967%
4.	Migration Velocity Based on Above Data	8.74 Cm/Sec.

TYPICAL COAL ANALYSIS

Proximate Analysis as Received

Moisture, %	5.51	Ash, %	23.28
Heating Value, BTU/Lb	10,613	Sulfur, %	1.20

Table 5 ELECTRICAL READINGS OF PRECIPITATOR "A" WITH AND WITHOUT SO_3 INJECTION WHILE BURNING LOW SULFUR COAL

1. WITH SO_3 INJECTION, 10/19/79

	DC-KVOLTS	AC-VOLTS	SPKS	AC-AMPS	DC-MA
Fields A	45	290	30	25	100
B	55	290	40-50	20	75
C	55	300	0-20	25	100
D	50	380	0-20	60	380
E	55	400	0-20	85	560
F	------Field Tripped Off ---------				

SO_3 Injection Rate - 23 PPM
Opacity - 5-7%

2. WITHOUT SO_3 INJECTION, 11/2/79

	DC-KVOLTS	AC-VOLTS	SPKS	AC-AMPS	DC-MA
Fields A	43	230	20	10	50
B	48	200	40	10	10
C	47	220	20	10	10
D	45	250	30	15	50
E	47	260	20	26	120
F	------Field Tripped Off ---------				

SO_3 Injection Rate - 0 PPM
Stack Opacity - 25-30%

ENHANCED PRECIPITATOR COLLECTION EFFICIENCIES THROUGH RESISTIVITY MODIFICATION

By: Dennis F. Mahoney
Apollo Technologies Inc.
Whippany, New Jersey 07981

ABSTRACT

High resistivity process dusts and fly ashes from low sulfur coal may be modified by chemical treatment to improve cold-side precipitator performance. A new series of additives which are effective in lowering resistivity is described. The additives are non-corrosive and of neutral pH. Laboratory resistivity test results are presented to show that treatment is insensitive to ash composition or coal variations. Reductions from 10^{11}-10^{12} ohm-cm to $<10^8$ ohm-cm have been achieved. Field results on a pilot precipitator and a utility boiler show power and opacity improvements.

INTRODUCTION

It is well known that ash from low sulfur coals presents collection problems for electrostatic precipitators (ESP's). This is especially true for those that were designed for high sulfur coal or those that are in poor mechanical condition. The reason for these collection difficulties is also well known: ESP's are most effective in collecting fly ash or other particles with resistivity values of about 10^{10} ohm-cm. Fly ash resistivity values are typically higher than this at cold-side temperatures; however, if sufficient sulfur is present in the coal, some of it will be oxidized during combustion to give SO_3 which may then condense on the fly ash surface to give a conductive film of sulfuric acid. Without this conductive film the resistivity will be a function of the particle composition and temperature. The resistivity will be determined by the pathway giving the lowest value. Above 400°F or in dry air the water layer is desorbed and the bulk resistivity values are measured. Bulk resistivity is inversely proportional to temperature while the surface resistivity is determined by adsorption mechanisms which are directly proportional to temperature. In general, fly ash bulk resistivities are too high for effective collection at cold-side ESP temperatures of 275-375°F, and with low sulfur coals the SO_3 and moisture levels are too low to reliably condition the ash at these temperatures.

In this paper the degradation mechanisms and some of the cures for ESP's collecting high resistivity fly ash will be briefly reviewed. The main portion of the paper will then report on new flue gas conditioners (FGC's) which are designed to overcome some of these difficulties.

EFFECT OF RESISTIVITY ON ESP OPERATION

Ash particle charging and the subsequent collection are determined by a number of factors including field strength, particle size and dielectric constant. Particle resistivity affects the collection process indirectly; as ash is collected a layer builds up on the plates, increasing the resistance across the precipitator. This lowers the voltage and in turn the collection efficiency.

The poor charge transfer of high resistivity ash also makes it more difficult to rap from the plates. Consequently, the clean plate powers seen when a unit comes back from an outage or after an air sweep will deteriorate with time. Table 1 shows the timewise degradation of an electric utility ESP collecting ash from low sulfur coal.

Table 1. EFFECT OF TIME ON ESP POWERS*

Days After Airsweep	Precipitator Powers (KVA)
0	179
1	174
2	148
3	160
4	134
5	79

* Operating temperature is approx. 275°F. Coal supply is 1.0-1.2% sulfur.

A number of different approaches have been used to counteract the effects of high resistivity ash. These include larger ESP's, hot-side ESP's, SO_3 injection and flue gas conditioning.

Increasing ESP size suffers from the obvious disadvantage of increasing construction costs. For example, a recent article (1) in the Journal of the Air Pollution Control Association estimated that ESP construction costs were $35/kW for high sulfur coal and $85/kW for low sulfur coal. This difference is due to the greater collection area and higher field strengths specified by ESP manufacturers for high resistivity ash.

Another mechanical alternative is the hot-side precipitator. By positioning the ESP before the air heater, these are designed to take advantage of the lower bulk resistivity in the 500-700° region. Unfortunately, a number of the low sulfur coals burned also have high bulk resistivities resulting in a similar problem.

One alternate approach to mechanical modifications is to lower the ash resistivity to match it to the particular ESP. As mentioned above this can be done with SO_3, NH_3 or other flue gas conditioners. Sulfuric acid has a higher dew point than water, but its performance is also limited. It is reported (2) to be most effective on basic ashes and to lose its effectiveness as the temperature increases. Other FGC additives are usually solutions which spray dry or vaporize in the gas stream. A well known example of these is Apollo's LPA-40®. FGC's are commonly molten salts which prevent rapper reentrainment or lower resistivity. As with sulfuric acid they may be ash specific or react with the ash to be deactivated.

RESULTS

In trying to develop an FGC additive to avoid these problems, a number of factors were considered including

- a liquid material for easy handling
- neutral pH to prevent corrosion or injury
- low feed rates for economy and ease of injection
- ash independence to minimize the effects of coal changes
- chemically inert to prevent pluggage or deactivation.

The results obtained can be understood in terms of physical properties, friability and resistivity lowering.

Physical Properties

The additives discussed here are similar to previous FGC's in that they are water based. They are also near neutral in pH. Ash reactive chemicals are not present or are in relatively low concentrations resulting in less interaction with the ash.

Deposit Friability

Under ideal conditions FGC's are sprayed into the gas stream evenly at low levels of 0.1-1% of the ESP ash loading. In practice, however, air heaters, cold spots and internal ductwork often provide sites where the additive and ash can collect together to give deposits which may disrupt or block the gas flow. If the two then react together or sinter, the deposit may become hard enough to resist easy removal. This behavior is most expected with high salt additives and reactive ashes.

With the new materials hard buildups do not occur. Laboratory simulations were made by mixing up to 5-10% of additives with ash and heating at 400°F for 4-16 hours. The result was a dry friable ash. In field trials a worst case situation was simulated by placing a cooled deposit probe directly in front of an FGC injection nozzle. This resulted in a moist deposit buildup which rapidly eroded after the FGC was shut off. By contrast a standard high salt FGC had a hard, sintered deposit which could only be removed with great difficulty.

Resistivity Modification

Even fly ashes with different compositions typically have very similar bulk resistivities. Figure 1 shows the dry air resistivity curves for two bituminous and one lignitic ash. Table 2 gives their elemental analyses.

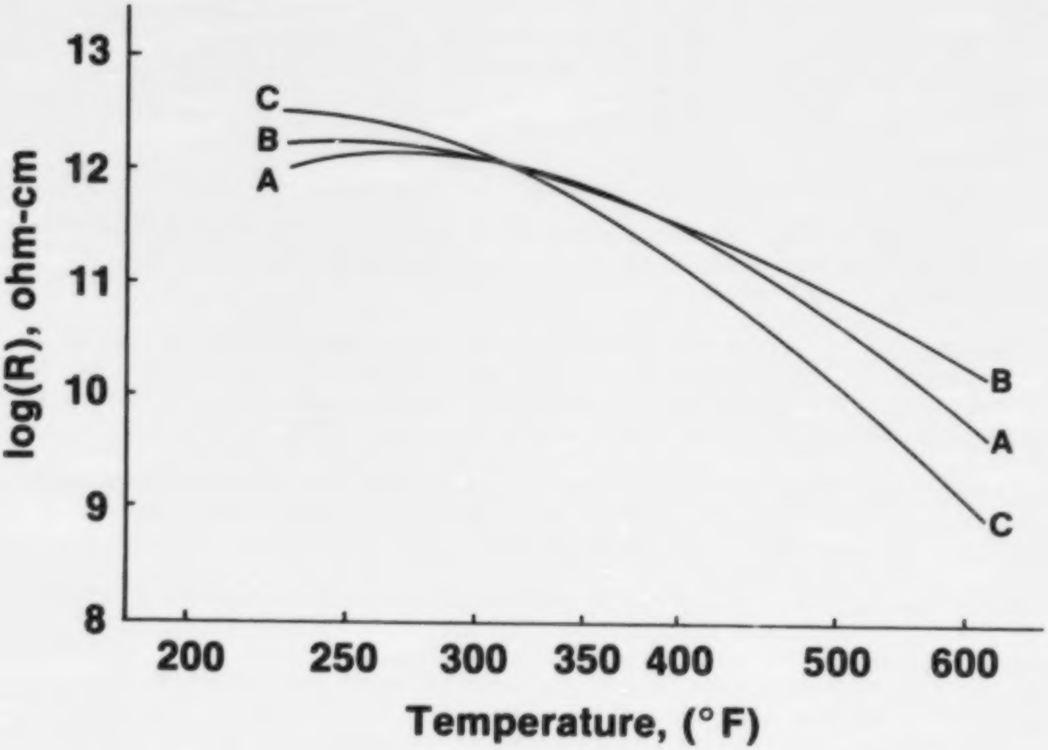


Figure 1. Resistivity Of Various Fly Ashes As A Function Of Temperature In Dry Air. A And C Are Bituminous Ashes And B Is Lignitic. Analyses Are In Table 2.

TABLE 2. FLY ASH COMPOSITION

Oxide, %	A	B	C
SiO_2	45.9	32.3	50.6
Al_2O_3	21.2	12.4	24.4
Fe_2O_3	11.2	5.6	6.4
CaO	2.2	12.4	2.1
MgO	0.5	6.3	0.8
Na_2O	0.3	4.2	1.3

Ashes A and C are bituminous while B is lignitic. The most noticeable difference in this composition is the higher calcium oxide level in B, but the iron levels also vary.

The surface resistivities of these ashes vary considerably as can be seen by Figure 2. Here the water is much more strongly adsorbed onto ash B, resulting in greater resistivity reductions. This is more representative of actual field conditions where flue gas moisture is 5-10%.

Conventional flue gas conditioners such as ammonium sulfate lower these resistivity values. Typically, 0.5% by weight on the ash lowers the resistivity by about one half order of magnitude.

Our first efforts to develop liquid modifiers yielded thermally unstable materials which were very effective at low temperatures but actually increased the resistivity at ESP temperatures. Figure 3 illustrates the effect of one of these formulations on ash A. Comparison of the curves at different moisture levels shows that the additive is much more effective than water at low temperatures, but that as the temperature increases the additive effectiveness drops off, and resistivity actually rises above the water conditioned values. The shaded areas in Figure 3 indicate regions in a normal ESP temperature range where resistivity reductions (T<300°F) and increases (T>300°F) would be seen.

This problem was overcome and treatment rates greatly reduced by reformulation. The curves in Figure 4 show the results of treating ash B. The shaded region between the untreated curves is bounded by the operating temperatures and moisture levels found in a typical cold-side ESP. Treated resistivity over this temperature range is low and essentially constant, with performance only beginning to drop off above 350-400°F. Lower treatment levels of less than 1% give similar curves but displaced slightly upward. Higher treatment values give off-scale resistivities.

In actual practice it may not be desirable to lower resistivity by such a large amount. Figure 5 illustrates the effect of a lower activity additive on two different fly ashes. Note that ash C is modified considerably over all ESP operating temperatures but that ash B, which has a lower resistivity, is only improved slightly in a narrower range. With sufficient experience these effects can be predicted by the ash elemental analysis and

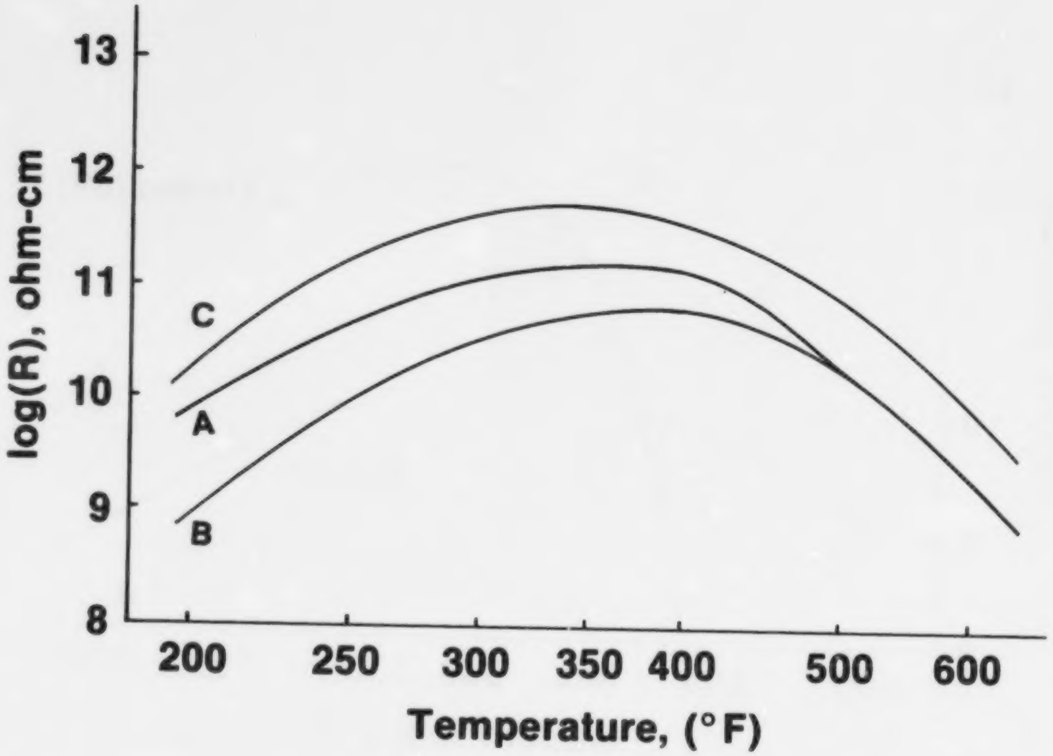


Figure 2. Effect Of Surface Conditioning By 20% H_2O In Air On Resistivity

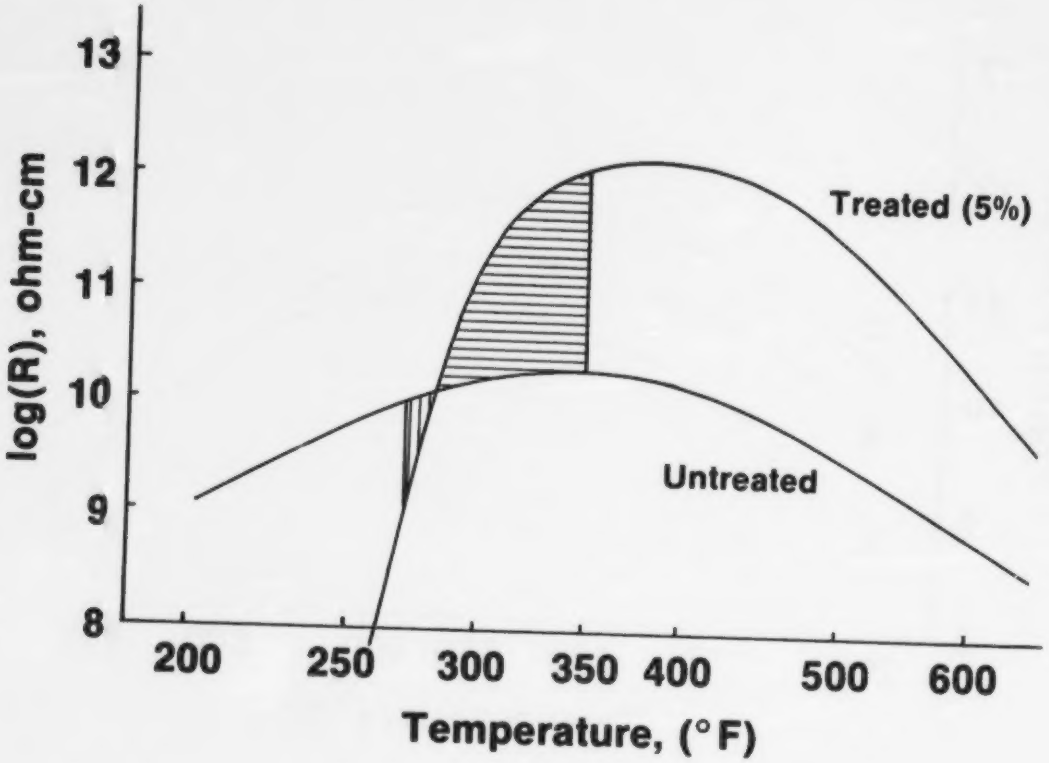


Figure 3. Effect Of Additive X On Ash Resistivity
See Discussion In Text.

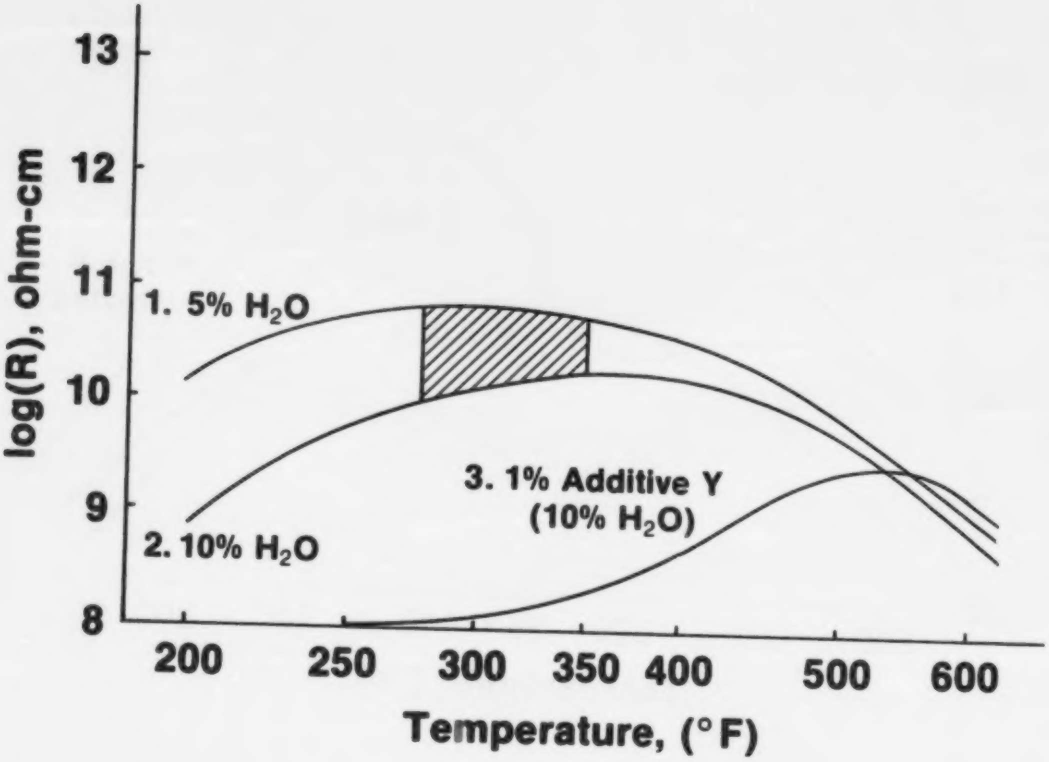


Figure 4. Effect Of Additive Y At 1% On Ash Resistivity As A Function Of Temperature 1. Untreated, 5% H_2O; 2. Untreated, 10% H_2O; 3. 1% Additive Y; 10% H_2O

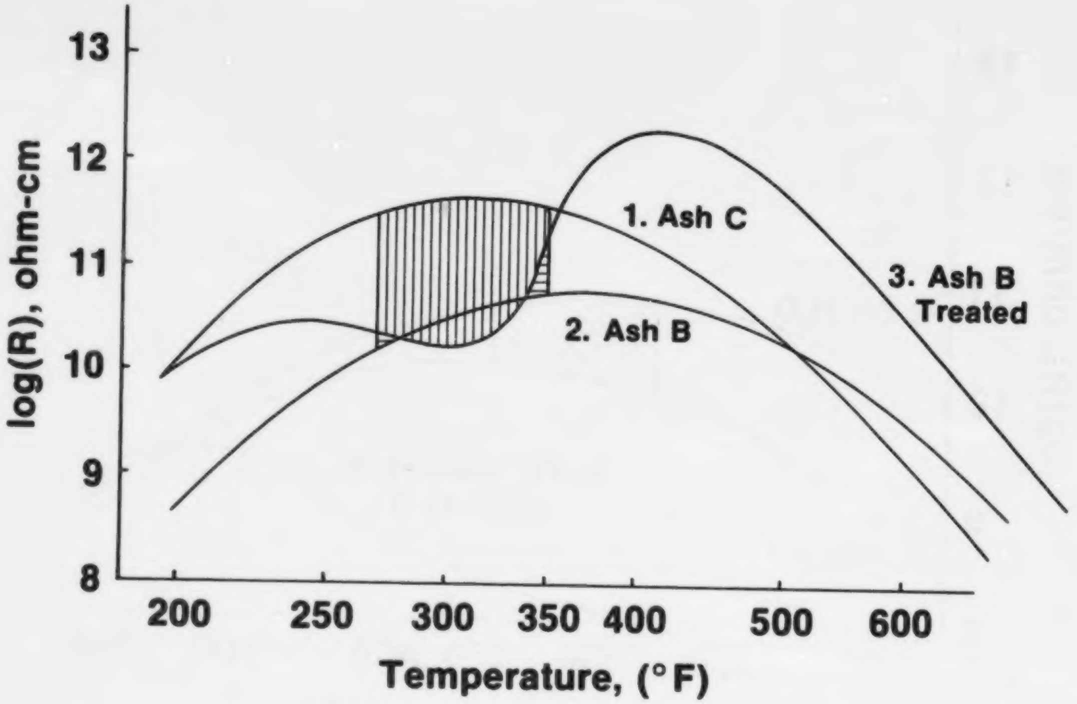


Figure 5. Effect Of Additive Z On Differing Fly Ashes Using 10% H_2O Atmosphere
Curve 1 - Ash C, Untreated;
Curve 2 - Ash B, Untreated;
Curve 3 - Ash C, treated

untreated resistivity curves.

Actual Precipitator Studies

Effects on an actual ESP bear out the resistivity reductions seen in the laboratory. Table 3 shows the effects on powers and opacities on a pilot ESP derated with high resistivity ash. Table 4 shows similar results on an actual field unit.

TABLE 3. PILOT PLANT RESULTS*

	Untreated	Treated	Percent Change
ESP Voltage (kV)			
• inlet	21	30	+42
• outlet	24	36	+50
Opacity	18	8	-55

* 270-310°F operating temperature, ash C

TABLE 4. FIELD ESP RESULTS

	Untreated	Treated	Percent Change
ESP Powers (kVA)			
• inlet	45	57	+27
• outlet	15	19	+27

In the field case testing was carried out at a time when ESP powers were not the limiting factor in collection efficiency; hence, the increase in powers did not materially lower opacity.

CONCLUSION

Ash resistivity can be an important factor in lowering ESP collection efficiency. The additives described here are independent of ash composition and can yield varying treated resistivity values depending on the additive chosen and amount used. The laboratory results have been substantiated in pilot plant and field precipitators.

A patent on this new process is being applied for and further results and discussion will be forthcoming.

ENDNOTES

1. Komanoff, C. Pollution Control Improvements in Coal Fired Electric Generating Plants: What They Accomplish, What They Cost. JAPCA. 30 (9) p. 1051 (1980).

2. Oglesby, S. et al. A Manual of Electrostatic Precipitator Technology, Part I: Fundamentals. 1970. pp 19, 173. Report No. APTD-0610 (Avail. NTIS).

DEVELOPMENT OF A NEW SULFUR TYPE ASH CONDITIONING

By: Robert H. Gaunt, Senior Research Engineer
Air Correction Division/UOP, Inc.
Norwalk, Connecticut 06856

ABSTRACT

Various types of chemical ash conditioning agents are used to alter flyash resistivity, and thereby improve electrostatic precipitator performance. Air Correction Division, UOP, Inc. has had experience with many chemicals and processes on a pilot and full scale basis. Sulfuric acid conditioning has advantages over other sulfur conditioning systems in availability, cost of chemicals, ease of handling, process control, and relative lack of corrosion problems. In the past, operating costs (power consumption) of sulfuric acid systems has not been particularly attractive in large power plants. ACD/UOP has developed a new system that utilizes the advantages of sulfuric acid while reducing the capital and operating costs to competitive levels with other systems. The new process utilizes existing energy in the compressed and heated plant combustion air. A prototype unit at a 46 MW station improved precipitator collection efficiency to 99.8% from 85.0% at an operating cost of $40.00 per day.

INTRODUCTION

As emission standards have become more stringent over the past decade, design and operation of pollution control equipment has become more and more critical. This particularly applies to the sizing and design of electrostatic precipitators (ESP's) for fossil fueled power plants.

One of the basic parameters that effects ESP performance is the resistivity of the flyash. ESP's operating on highly resistive flyash ($>10^{10}$ ohm-cm) (see figure 1) are faced with problems of ash build up on electrodes, and poor electrical operating characteristics such as low voltage-current, back corona, and early sparking. (1) (see figure 2) These problems can, to some extent, be dealt with by specific ESP designs for highly resistive ash. However, this increases the size and complexity of an ESP and adds considerably to the cost.

The resistivity of the ash is dependent on a number of factors which can be altered or used advantageously. One is temperature. Typical resistivity temperature curves are shown in figure 1. The conventional ESP is placed after the air preheater which frequently is near the point of highest ash resistivity. Moving the ESP to the hot side of the preheater overcomes this problem, but adds to the ESP size since greater gas volume must be handled, and structures are more complex to deal with higher temperatures. Hot side ESP's are not a cure all since they too can have resistivity problems, particularly with low sodium coals.

A second approach to processing with highly resistive ash is to chemically alter the flyash and thereby change the resistivity to a more favorable range. Chemical conditioning agents can be introduced in the power plant's process stream in several places. The agent can be added to the coal, injected in the combustion zone, or injected in the flue gas stream. The first two locations may create slagging problems in the boiler. Flue gas injection, generally involves more equipment, but has fewer operational difficulties.

The chemicals typically added to alter resistivity for cold side ESP's are sulfur compounds, such as, sulfur-trioxide (SO_3), as well as ammonia (NH_4), water, and other proprietary chemicals. Sodium compounds are generally used to condition hot side ESP's. Air Correction's experience with cold side conditioning is the subject of this report.

ASH CONDITIONING

Two mechanisms are involved in passing an electric charge thru flyash. Volume conductivity is dominant at temperatures above 450°F. (2) As the temperature increases, the resistivity of the ash particle drops allowing passage of an electric current thru the body of the particle. As the temperature falls below 350°F, surface conductivity becomes dominant. In this process the charge is carried by the adsorbed chemical impurities on the surface of the particle rather than thru the particle. Since this temperature break is also at the upper range of cold side ESP application, most cold side conditioning agents are adsorbed by the flyash and act by improving surface conductivity.

In the 1960's it was found that the addition of sulfates (SO_4) greatly increased the conductivity of flyash. This happens naturally when most coal is burned. Sulfur is usually present in all coal to some degree. When burning it forms sulfur dioxide (SO_2) and a few percent of sulfur trioxide (SO_3). (2) The SO_3 in combination with the water in the flue gas acts as a natural conditioning agent with most flyash. As power plants began to burn low sulfur coal (under 1.5% to 1.0%) to meet SO_2 emission requirements, the amount of SO_3 was not enough to keep the ash resistivity in a reasonable range for good operation of ESP's. This resulted in increased particulate emissions as the sulfur emissions fell.

ACD/UOP EXPERIENCE

Interest in ash conditioning began to develop with the need to burn lower sulfur coals. ACD first tried the obvious step of injecting SO_3 in a flue gas stream on an experimental basis. This produced improvement in ESP operation and also pointed out the difficulties in handling SO_3. The test system used stabilized SO_3 liquid, heated to a vapor, and injected it in the flue duct. However, when cooled below 90°F, SO_3 starts to solidify in storage tanks, pumps, heat exchangers, pipes, etc. Heating it as a solid frequently causes it to sublime in which case, the gas may be trapped by the solid and under high pressure. As a gas it reacts extremely exothermically with water. With water it forms fuming sulfuric acid which is extremely corrosive until sufficient dilution occurs. The SO_3 studies were not carried past the experimental stage.

Ammonia was tried and found to produce improvement in ESP operation in a few special instances. Water was also tried but was found to be ineffective except in very large amounts or at very low flue gas temperatures. Sulfur trioxide was almost always effective, but a more practical way to introduce it in the flue gas was required.

One novel method tried was to pass a slip stream of flue gas through a catalyst bed to increase the SO_3 content, and then pass it back into the flue gas. Ash plugging problems were encountered and operation on extremely low sulfur coal was not feasible. Another method was to take liquid SO_2, heat it to a vapor, pass it over a catalyst bed to convert a large quantity to SO_3, and inject it into the flue gas. While this looked promising, a third method looked even better. This was to vaporize liquid sulfuric acid (H2SO4) and thermally dissociate a portion of the vapor to SO_3 and water ($H2SO4 \rightleftharpoons H2O + SO_3$) The temperature required to vaporize the acid was around 450°F to 500°F. Then the vapor was passed over a superheater to raise the temperature to around 800°F to 900°F. This has the advantage of using sulfuric acid as a conditioning agent. It is readily available, comparitively cheap, and fairly safe to handle. As a common industrial reagent, there is a large amount of technical experience on its handling, storage, transport, and use. With the 93% (66°Baume) concentration used, serious corrosivity exists only when changing state from a liquid to a gas or the converse. Further work proved that acid dissociation is not required, and the superheater could be eliminated.

The use of sulfuric acid vapor as a conditioning agent produces the same effect as conditioning with SO_3 and has some handling and process advantages. When SO_3 is injected into a flue gas stream, it immediately reacts with the moisture in the gas stream to form H2SO4, which is adsorbed on the flyash. Injecting H2SO4 to start with has the identical effect on the ash. It has been found that the lances and nozzles used to inject SO_3 must be kept at 800°F or higher to keep the SO_3 from immediately combining with the moisture at the nozzle and thereby corroding it quickly away. In contrast, the nozzles and lances used to inject sulfuric acid vapor need only be kept above the vapor dew point, generally under 400°F. This can be accomplished with the heat of the vapor with short runs that are well insulated. Heat tracing is not required. A flow diagram of this conditioning system is shown in figure 3. This system was installed at Cameo Station, Public Service Company of Colorado in 1968, and resulted in the first utility order for a commercial ash conditioning unit in the United States.

At this point it would be good to reexamine sulfur emissions and the operation of sulfur conditioning systems. At first glance, it appears that with sulfur conditioning, sulfur is being added to replace that reduced by burning low sulfur coal. This is not the case since most sulfur from coal combustion is emitted in the form of SO_2, which is released to atmosphere. Large percentages of SO_3 or H2SO4 are absorbed on the flyash and collected by the ESP. This is confirmed in EPA Report, EPA-600/7-79-104a. The acidity of the ash increases but not greater than that from burning high sulfur coal.

For determining the conditioning feed rate two methods are generally used. Sampling the stack gas and operating at a rate just below that where sulfur emissions begin to increase is possible. The second is considerably less difficult. Assuming the plant has been operating without conditioning, injection is initiated at a low rate,and slowly increased over a period of at least 24 hours. The ESP voltage-current readings will increase as the conditioning rate increases up to the point of acid carry over. The ESP readings then stabilize or fall off slightly and a blueish tint to the plume may be noticiable. The optimum conditioning rate is slightly below this point. It should be noted that it may take 18 to 24 hours for the full effect of conditioning to take place.

It has been ACD's experience that 12 to 20 ppm of acid is all that is required to condition the ash. Most of our units are sized for 30 ppm maximum and some for 45 ppm for unusual conditions or customers request. This extra capacity has never been required and is a margin of safety. To date no corrosion problems have occurred to the flue ducts or ESP internals due to the ash conditioning.

ACD DEVELOPMENT PROGRAM

The early work by ACD in sulfuric acid conditioning resulted in ACD's patented sulfuric acid vaporizing system. As is seen in figure 3, clean air is compressed to around 2 psig by a blower; the air is heated to 485°F by an electric air heater and mixed with a metered amount of acid in a glass lined packed column. The acid is pumped from a day tank and injected into the vaporizer by a metering pump. All equipment is mounted on a single skid near the flue duct. From the vaporizer the acid vapor is carried in a short length of glassed steel pipe to the stainless steel injection lances where it is dispersed in the flue gas.

This system has been developed to be quite reliable. Changes from early units have simplified controls and improved materials to withstand system upset conditions without damage. These units are most attractive to smaller plants (see table 1). Their performance is quite good. The main draw back is their relatively high operating cost due to electric power consumption heating the process air.

ACD recognized the operating cost problem and set out to develop a system that would utilize sulfuric acid with its advantages, but do so in a more economical manner. The first approach was that of direct spray into the flue duct. Acoustic atomizing nozzles were used to produce a very fine "fog" of atomized liquid sulfuric acid. This was by far the simplist and cheapest approach. In still air these nozzles worked quite well, however, after tests in three locations, it was determined that the acid was not dispersing properly in the flue ducts and was in fact wetting streams of flyash that passed near the nozzles. This caused the locally damp ash to adhere and build up on the first surface it came in contact with. Usually, this would be turning vanes or the perforated plate across the face of the ESP. No practical way to prevent this was found and work on the direct spray approach was suspended.

The next step was to try to maintain the lance dispersion method of the vaporizer system with the efficiency of the direct spray approach. It was decided to try spraying the acid in a slip stream of hot air or gas in a controlled manner so that the acid would vaporize and could be injected into the flue duct as a vapor. The initial step was to develop a spray chamber to vaporize the acid. This was done with a laboratory model using air and water. One requirement was to vaporize the acid completely before it came in contact with any surface so as to eliminate corrosion problems. A cylinderical chamber was devised with the air flow in and out of tangential openings and the acid sprayed down the center axis from one end. (see figure 4). After a working model was developed in the lab, a chamber was made up to try with acid. This project was done at a power plant with one of our vaporizer conditioning units so the acid vapor could be fed into the flue duct and collected by their ESP. The vapor system rate was turned down accordingly when the chamber was in operation. The hot air for the chamber was taken from the hot air side of the Lundstrom type air preheater. The amount of air is about 14-15 scfm per megawatt of power produced. This is below the normal leakage rate associated with a Lundstrom air heater. Using this test setup, exact chamber, nozzle, and internal flow device dimensions were developed for the chamber; and air flow, temperature, and acid flow rate limits were developed.

When the basic spray chamber was perfected the next step was to incorporate it in an operating system. A prototype system was built and installed at the same plant so that the new system could be tested with the vaporizer system as back up and as a comparison. This new system consists of a control and metering pump skid, two chambers, two lances, and the associated air and acid piping. It is shown in figure 5. This system was operated by both ACD/UOP and power plant personnel to discover any operational bugs and correct them prior to offering the system as part of our product line. Also, life expectancy of the components could be determined and improved if necessary. The only problems which appeared were in the area of automating the shut down procedure to prevent acid from sitting stagnent in the hot lines near the spray nozzle. This was accomplished with an automatic air purge.

The new process is called the SAAC System (Sulfuric Acid Ash Conditioning). It avoids several limitations of the vaporizer column. It can handle dirty process air. The flow thru the chamber is clear so most particulate is carried along with the air. This is not the case with a packed vaporizer column which must have filtered air and quite clean acid. The chamber can operate over a wide temperature range (500°F to 750°F), where the vaporizer glass and teflon must be closely held between 475°F to 500°F for proper operation. No expensive materials are required for the chamber. The tangential air flow keeps the acid out of contact with the chamber until it is vaporized. The only exotic material used is the acoustic spray nozzle which is made out of tantalum. This is required since it is at a liquid/gaseous interface where extreme corrosion occurs.

In operation the SAAC system avoids the operational expense of our previous system. Hot air is supplied by the existing plant air heater. In some cases a start-up trim heater may be recommended depending on operating conditions. The pressure differential between the air heater outlet and inlet to the ESP produced by the plant combustion air blowers is sufficient for the process so no blower is required. The compressed air for the nozzles is one cfm per nozzle.

The sulfuric acid is kept as an easily handled ambient liquid up until mixing with hot air. This is done adjacent to the duct work to keep the vapor piping as short as possible. The control and metering pump skid can be mounted remotely at a convenient location.

In summary, ash conditioning with sulfur compounds is the most successful method of lowering the resistivity of high resistivity ash to a range needed for good electrostatic precipitator operation. Air Correction Division of UOP (ACD/UOP) has been a leader in researching this field and led the field in early pilot work. ACD/UOP has offered a reliable, effective ash conditioning system over the past decade. Now ACD/UOP has developed a new sulfur conditioning process that retains the advantages of the old system and has greatly lowered operating costs associated with sulfur conditioning.

REFERENCES

1. White, H.J. Resistivity Problems in Electrostatic Precipitators, APCA, Vol 24, No. 4, April 1974.

2. Oglesley, S. Jr. and Nichols, G.B. Electrostatic Precipitation. New York, N.Y., Marcel Dekker, Inc. 1978.

TABLE 1

					EFFICIENCIES (%)	
UTILITY	UNIT	MW	ACFM	TEMP $(^{\circ}F)$	WITHOUT CONDITIONING	WITHOUT CONDITIONING
Public Service Co. of Colorado - Cameo Station	2	44	221,300	280	50.0	94.0
General Motors Corp.	1&2	--	150,000	350	73.0	93.3
Chevrolet Detroit-Forge	7&8	--	150,000	350	48.4	93.3
Public Service Co. of	2	46	261,000	315	51.5	97.5
Colorado-Arapahoe Station	3	44	250,000	350	42.2	94.8
Luzern Electric Div., UGI Corp. Hunlock Creek Station	6	46	225,000	350	85.0	99.8
Pennsylvania Electric Co.	9	--	270,000	400	90.0	99.1
Front Street Station	10	--	270,000	400	91.0	99.2
Detroit Edison	23	--	-------	---	90.1	94.4
Pennsalt Plant	24	--	-------	---	87.4	93.0
Wyandotte, Michigan						

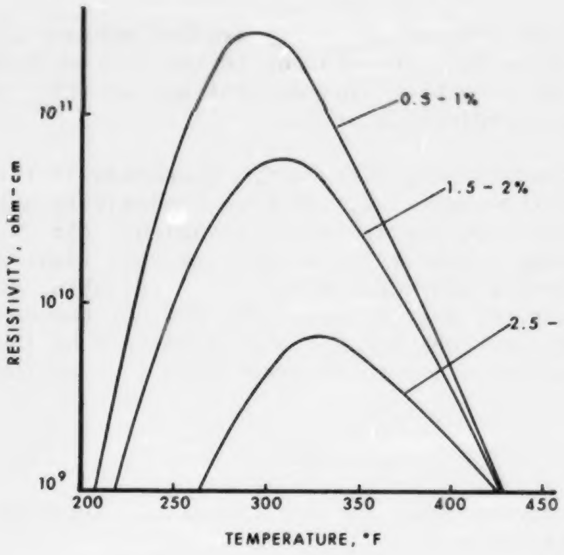


FIGURE 1

RESISTIVITY OF FLYASH FOR VARIOUS SULFUR CONTENTS

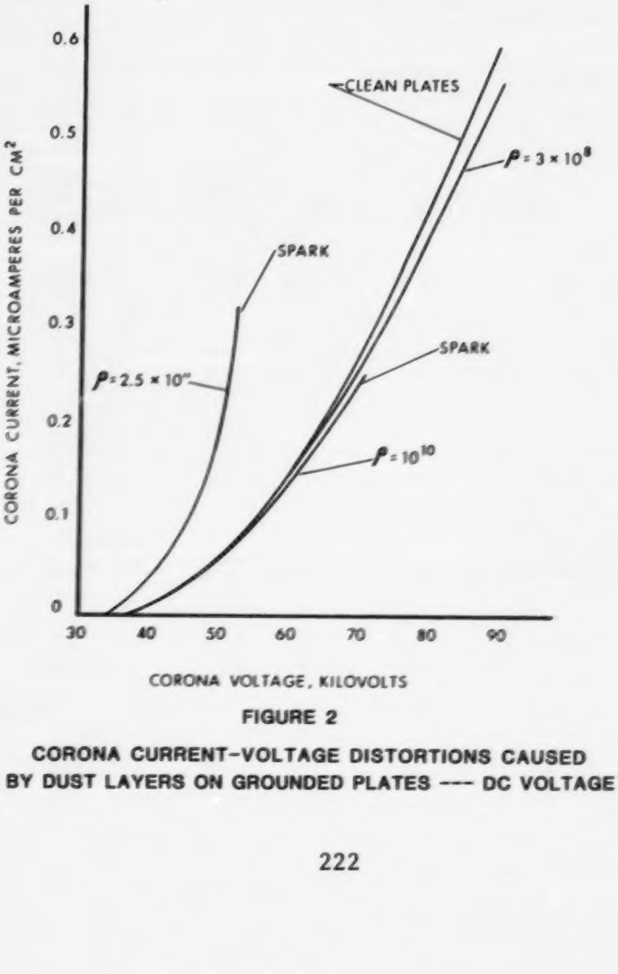


FIGURE 2

CORONA CURRENT-VOLTAGE DISTORTIONS CAUSED
BY DUST LAYERS ON GROUNDED PLATES --- DC VOLTAGE (1)

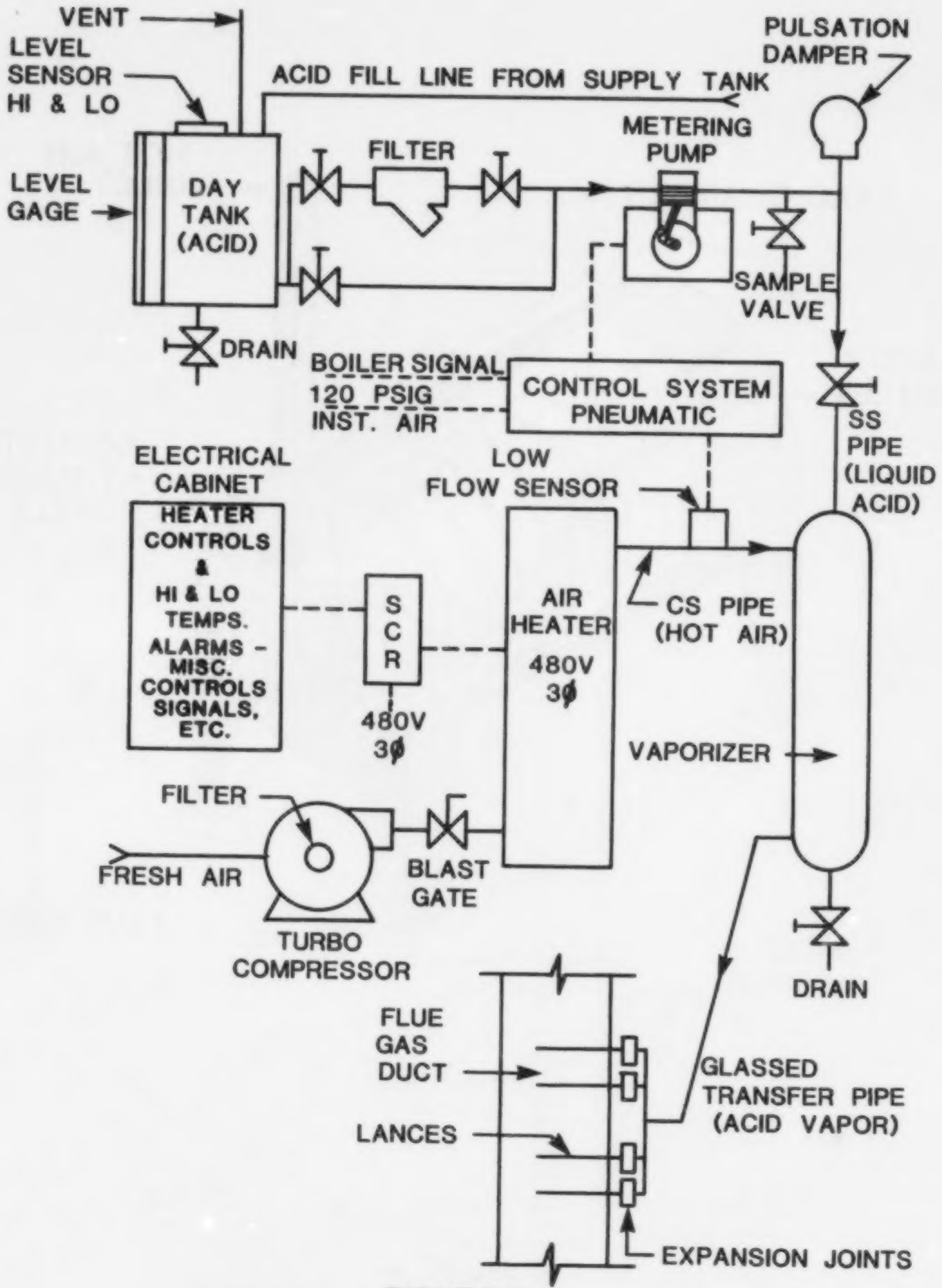

VENT
LEVEL SENSOR HI & LO
ACID FILL LINE FROM SUPPLY TANK
PULSATION DAMPER
METERING PUMP
FILTER
LEVEL GAGE
DAY TANK (ACID)
SAMPLE VALVE
DRAIN
BOILER SIGNAL
120 PSIG INST. AIR
CONTROL SYSTEM PNEUMATIC
SS PIPE (LIQUID ACID)
ELECTRICAL CABINET
HEATER CONTROLS & HI & LO TEMPS. ALARMS - MISC. CONTROLS SIGNALS, ETC.
LOW FLOW SENSOR
S C R
480V 3ϕ
AIR HEATER
480V 3ϕ
CS PIPE (HOT AIR)
VAPORIZER
FILTER
FRESH AIR
BLAST GATE
TURBO COMPRESSOR
DRAIN
FLUE GAS DUCT
LANCES
GLASSED TRANSFER PIPE (ACID VAPOR)
EXPANSION JOINTS

FIGURE 3
TYPICAL VAPORIZER SYSTEM FLOW DIAGRAM

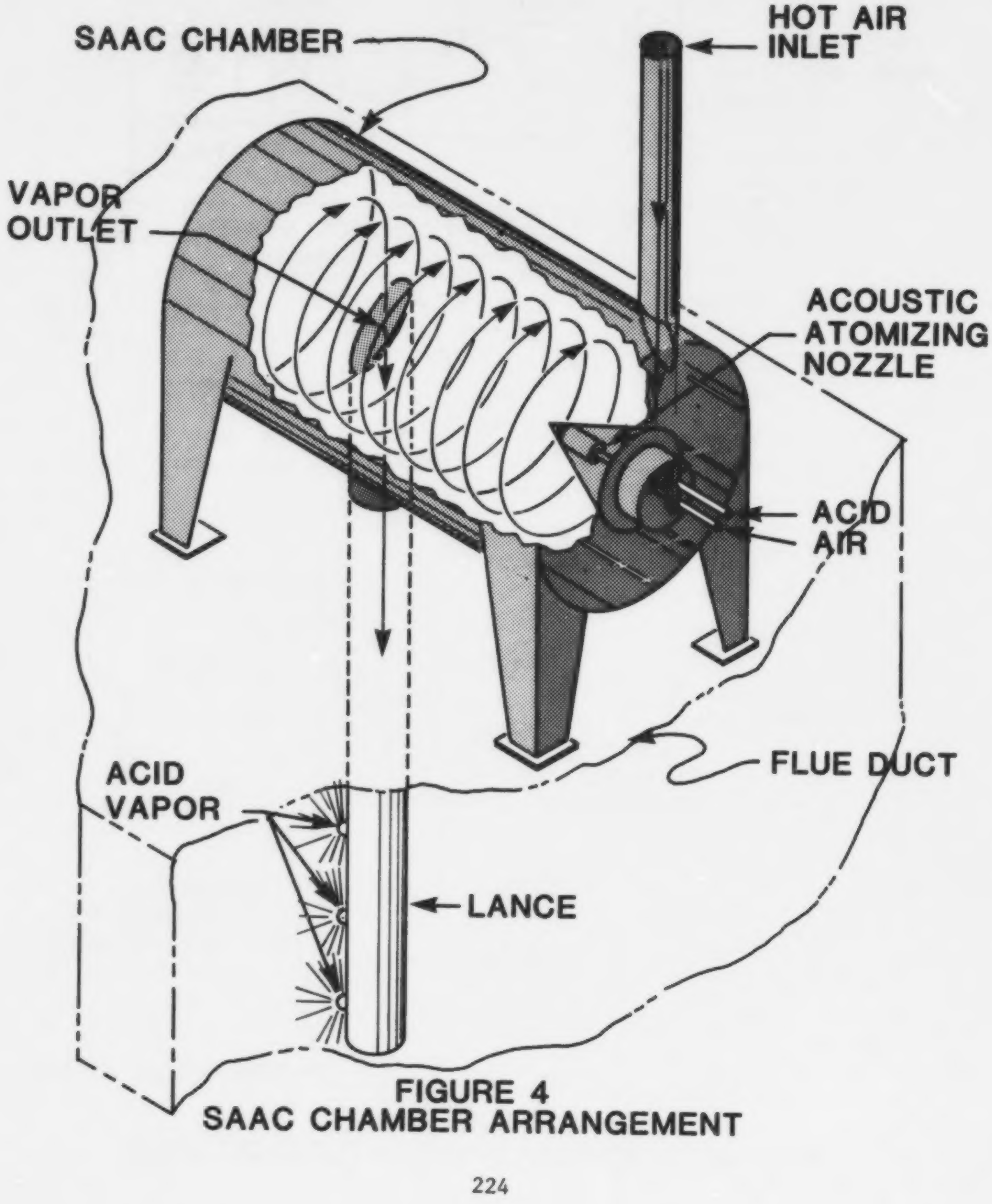

SAAC CHAMBER
HOT AIR INLET
VAPOR OUTLET
ACOUSTIC ATOMIZING NOZZLE
ACID
AIR
FLUE DUCT
ACID VAPOR
LANCE

FIGURE 4
SAAC CHAMBER ARRANGEMENT

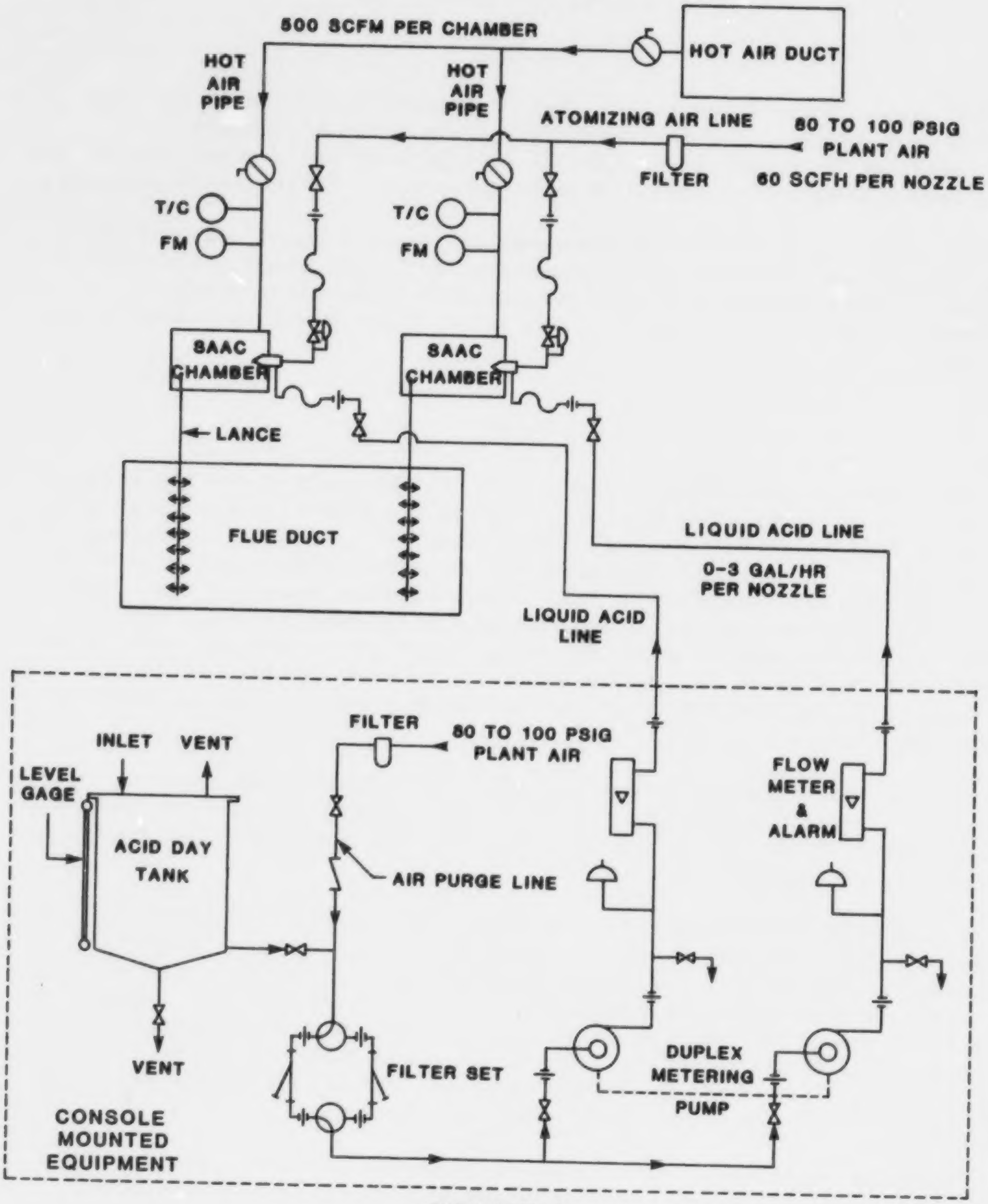

500 SCFM PER CHAMBER
HOT AIR DUCT
HOT AIR PIPE
HOT AIR PIPE
ATOMIZING AIR LINE
80 TO 100 PSIG PLANT AIR
FILTER
60 SCFH PER NOZZLE
T/C
FM
T/C
FM
SAAC CHAMBER
SAAC CHAMBER
LANCE
FLUE DUCT
LIQUID ACID LINE
0-3 GAL/HR PER NOZZLE
LIQUID ACID LINE
FILTER
80 TO 100 PSIG PLANT AIR
INLET
VENT
LEVEL GAGE
ACID DAY TANK
AIR PURGE LINE
FLOW METER & ALARM
VENT
FILTER SET
DUPLEX METERING PUMP
CONSOLE MOUNTED EQUIPMENT

FIGURE 5
TYPICAL SAAC SYSTEM FLOW DIAGRAM - 2 CHAMBER

OPERATING EXPERIENCE WITH FLUE GAS CONDITIONING SYSTEMS AT COMMONWEALTH EDISON COMPANY

By: L. L. Weyers, R. E. Cook
Commonwealth Edison Company
Chicago, Illinois 60690

ABSTRACT

The use of western low sulfur coal, to reduce sulfur oxide emissions, has resulted in decreased electrostatic precipitator collection efficiencies. In an effort to restore precipitator performance, a flue gas conditioning program was established by the company in the early seventies.

This paper is a history of Commonwealth Edison Company's experience with flue gas conditioning agents over the last eight years. Extensive testing of these systems has supplied valuable information which is presently being used as a basis in design of future plant additions to our systems.

TEXT

The change to low sulfur western coals in the early seventies resulted in unacceptable particulate emissions due to the high resistivity of the fly ash. This condition required that Edison either install additional precipitator sections, new precipitators, or reduce the resistivity of the fly ash by the addition of chemicals. Each unit was examined individually and two hot side precipitators and one cold side were installed for low sulfur coal. The remaining twelve units, which were scheduled to burn low sulfur coal, had large enough precipitators to meet particulate limits if the resistivity of the fly ash could be improved and the boiler operated at design gas flow.

Edison, after testing several proprietary chemicals and various SO_3 injection systems, including a liquid sulfur trioxide system, decided that the most cost effective and potentially most reliable system was the sulfur burner type SO_3 system.

The experience gained from a pan-type sulfur burner installed on a 230 megawatt pulverized coal fired boiler at State Line Station in 1973 indicated a considerable reduction in particulate emissions could be expected. The precipitator efficiency increased from 84% to 97% when feeding 50 ppm of SO_3 and the corona power input exhibited a great improvement with SO_3 injection. By reducing the sparking in the precipitator, the power input level was increased from 25 watts per 1,000 ACFM to 250 watts per 1,000 ACFM; a ten-fold increase.

Operating experience with the pan-type burner, however, was not good. The sulfur feed method was unreliable and required extensive operator attention. In addition, there was little turn-down capability of the burner. It was possible to increase the turn-down capability to five to one. However, because of the uncertainty of future coals for the stations, it was felt that any flue gas conditioning system must be automated, simple to operate, and have a turn-down ratio of at least ten to one.

Wahlco, Inc., had submitted a proposal for a sulfur burning type flue gas conditioning system. Their system utilized a drip-type burner with a guaranteed ten to one turn-down ratio. The flue gas conditioning system, shown schematically in Figure One, was quite simple and had the advantage of being compactly mounted on a skid. This was an important consideration because previous experience had shown that the SO_3 source should be located as close to the injection probes as possible, to minimize heat loss in the piping system. In addition, their system, because of its compactness, could be installed in a rather small area.

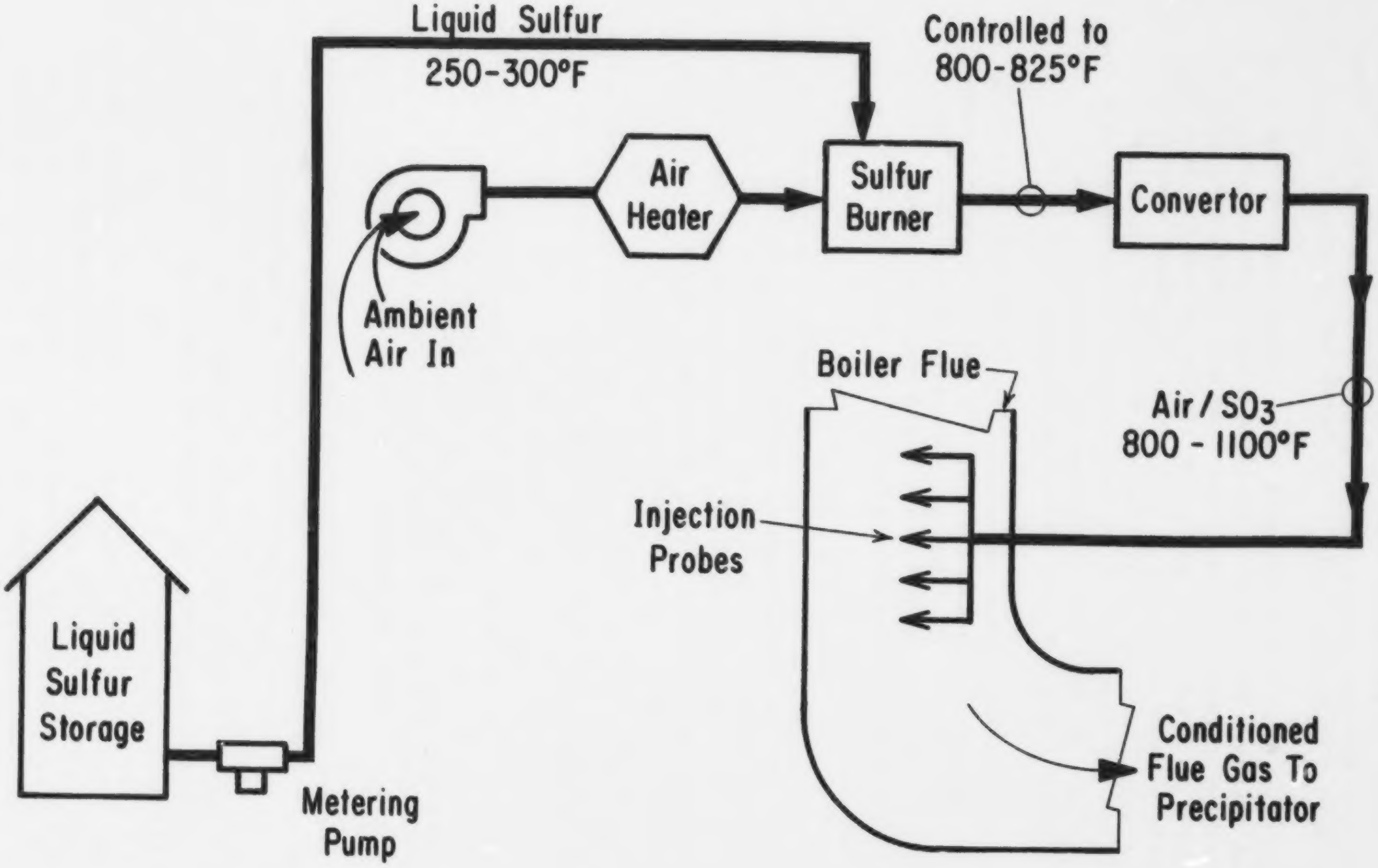
A flue gas conditioning system was ordered for State Line Unit Three in 1974, but due to commitments to the Illinois EPA and the City of Hammond EPA, Edison was required to order flue gas conditioning equipment for eleven other units, totaling approximately 3,000 megawatts before the first system at State Line could be tested. All of these units had to be operational before June, 1976.

As with any new system, a certain number of problems were expected. The first to occur was the sulfur pumping system. Liquid sulfur requires a temperature range of 245°F to 310°F. Below 245°F it solidifies, and above 310°F it becomes extremely viscous. Many pump failures occurred which were usually attributed to the pump diaphragms being ruptured when bringing the system on line. These failures also occurred when the sulfur in the stand-by pump was allowed to solidify. By changing to steam jacketed pumps instead of electrically heated, and adding additional steam tracing and insulation on the pump piping and valves, the problem was corrected.

The next problem that occurred was the failure rate of the calrod air heaters. Even though Edison had specified an in-line spare heater, the failure rate often resulted in a burner being out-of-service for replacement of the heater elements. This problem was corrected by improving the quality control at the heater manufacturer's plant.

The third problem did not become apparent until after several months of operation. Some of the injection probe insulation, which was covered by fiberglass and epoxy, was being eroded by the fly ash particles. These failures occurred in installations where the probes were experiencing high gas velocities because of their location in the duct-work. Only a few units had this problem, and it was corrected by installing a steel liner over the insulation.

The original specification for the sulfur burner units called for a capability of producing at least 60 ppm of SO_3 with a turn-down ratio of ten to one. The 60 ppm was based on precipitator test results with the original burner and Arch Mineral Coal. An analysis of Arch Mineral and


Liquid Sulfur
250-300°F
Controlled to
800-825°F
Air
Heater
Sulfur
Burner
Convertor
Ambient
Air In
Boiler Flue
Air / SO3
800 - 1100°F
Injection
Probes
Liquid
Sulfur
Storage
Metering
Pump
Conditioned
Flue Gas To
Precipitator

FLOW DIAGRAM

FLUE GAS CONDITIONING UNIT

Figure 1

other coals utilized by Edison is shown in Table One. When the Wahlco System became operational, precipitator tests indicated that less than 20 ppm of SO_3 was the optimum feed, even on Arch Mineral Coal with its extremely high resistivity (greater than 10^{13} ohm-cm). The only explanation for this change was the much more extensive injection probe system installed by Wahlco which resulted in better SO_3 distribution.

As more sulfur burners became operational at the various stations, it became apparent that some low sulfur coals required very little SO_3 to improve or optimize precipitator performance. The oversized burners, therefore, aggravated the problem since operation at minimum sulfur feed rate often created a condition whereby the system would trip-out due to low temperatures which indicated flame failure of the burner.

The coals that need little SO_3, such as Decker and Big Horn, fortunately also have a very low ash content. Therefore, even if the precipitator was not at optimum performance levels because of the sulfur burner being out-of-service, the low inlet dust loadings resulted in acceptable particulate emissions. Consequently, many of the sulfur burners were left in a "stand-by" mode of operation when the stations were burning Decker or Big Horn coal.

This problem was examined in detail in 1977 when an experimental program was undertaken to determine quantitive relationships between precipitator performance parameters and other system variables at State Line Station, Unit Three. This is a Combustion Engineering twin furnace steam generator. The Research Cottrell precipitator was designed for 98% collection efficiency with a gas volume of 657,700 ACFM at 305°F and has a SCA of 137 square feet/1,000 ACFM. Investigated were the effects of variation in boiler steaming rate, the SO_3 injection rate, and the relationship derived from the individual automatic voltage control operating parameters of voltage, current and spark rate. The independent variables of the experiment were the SO_3 injection rate and the boiler steaming rate. The AVC parameters are, in effect, dependent variables for two reasons. First, they control themselves in secondary currents. Second, the currents and spark rates are affected by the SO_3 injection.

Contrary to normal operation of the boiler, the boiler steaming rate was held constant. The SO_3 injection rate was then held constant for long periods of time to observe the effects. However, several times during the test period the steaming rate was reduced significantly. The transmissometer readings, however, remained constant at a relatively low level.

A data acquisition system was installed and operated for a seven day period. During this time, two different periods of "constant coal" were arranged utilizing Decker and Arch Mineral. These coals were chosen because of their chemical differences as shown in Table One. Arch Mineral, with its low sodium content, results in very high resistivity fly ash; while Decker, with its relatively high sodium content, results in a fly ash resistivity below 10^{11} ohm-cm.

TABLE 1. TYPICAL COAL AND ASH ANALYSIS

"As Received" Coal Analysis (% By Weight)

	Decker	Arch Mineral	Big Horn
Moisture	24.2	13.8	23.5
Sulfur	0.4	0.6	0.5
Ash	4.3	12.0	5.4
BTU/lb.	9,511	9,760	9,329

Ash Analysis (% By Weight)

Silica	23.6	35.5	29.8
Alumina	20.5	18.1	17.3
Iron Oxide	7.5	14.6	9.0
Calcium Oxide	17.7	17.0	15.6
Magnesium Oxide	3.6	3.3	4.8
Potassium Oxide	0.6	1.2	1.2
Sodium Oxide	6.4	0.7	2.5

The data acquisition system was designed to collect data on a sample basis every five minutes from six different AVC's and three other analog signals representing the outputs of the transmissometer, a boiler steam rate measurement and an SO_3 injection rate measurement. Every half hour (or six five-minute samples) a block of data was transferred from the computers memory and recorded on the cassette tape contained in the unit.

The data indicated that when the system performance is measured by the optical transmissometer, there is an optimum value for the SO_3 injection rate. In particular for the coals tested, including a blend of the two coals, the optimum injection rate was in the range of five ppm to 20 ppm. Values above 20 ppm were definitely shown to be less effective in reducing opacity. The effect of SO_3 conditioning on opacity with Decker and Arch Mineral coals is shown in Figure Two. The higher ash content of the Arch Mineral coal results in an overall higher opacity as would be expected. The optimum SO_3 injection rate for Decker and Arch Mineral based on this test period was five ppm and 20 ppm respectively.

The data also clearly indicated that the optimal value of SO_3 did not occur when the AVC currents were highest or when the spark rate was a minimum. Figure Three shows the current, opacity and SO_3 feed. As can be seen, the opacity decreases with increasing SO_3 feed rate and increasing power until approximately 20 ppm of SO_3 is injected. Further increases in the SO_3 feed rate results in additional power input; however, the opacity also increases.

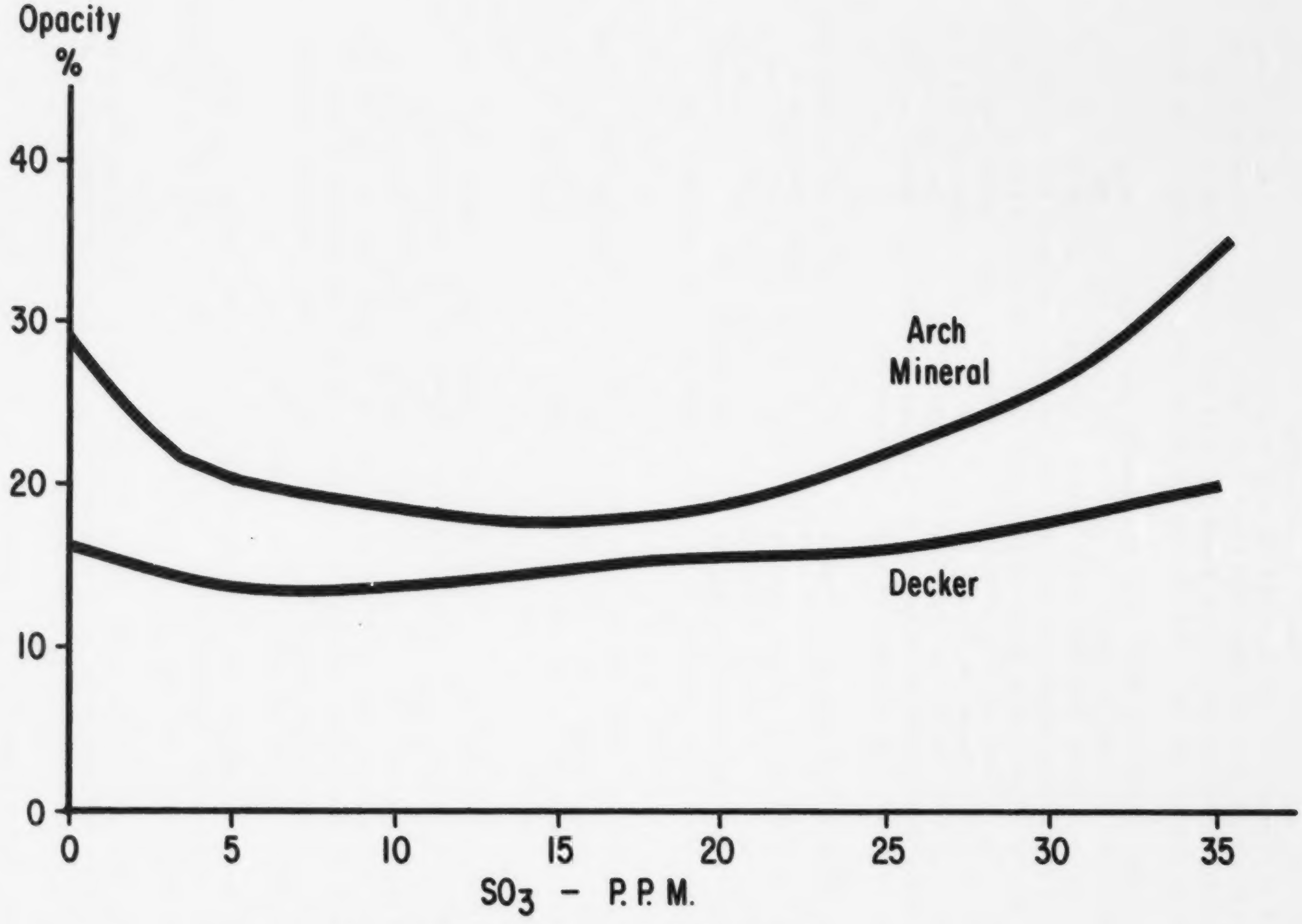
In October of 1979, extensive testing of Crawford Station Unit Seven precipitator was begun with varying SO_3 feed rates. The coals used for these tests were Decker and Big Horn, and their analysis is shown in Table One.

A total of 24 tests were conducted on Crawford Unit Seven. This is a 220 megawatt unit with a Combustion Engineering twin furnace steam generator. The Research-Cottrell precipitator was designed for 98% collection efficiency with a gas volume of 690,000 ACFM at 300°F and has a SCA of 147 square feet/1,000 ACFM. The precipitator was tested at 200 megawatts to obtain near design gas volume and the SO_3 feed rate was adjusted in increments from 0 to 35 ppm. The SO_3 feed was held constant for a minimum of twelve hours prior to each test.

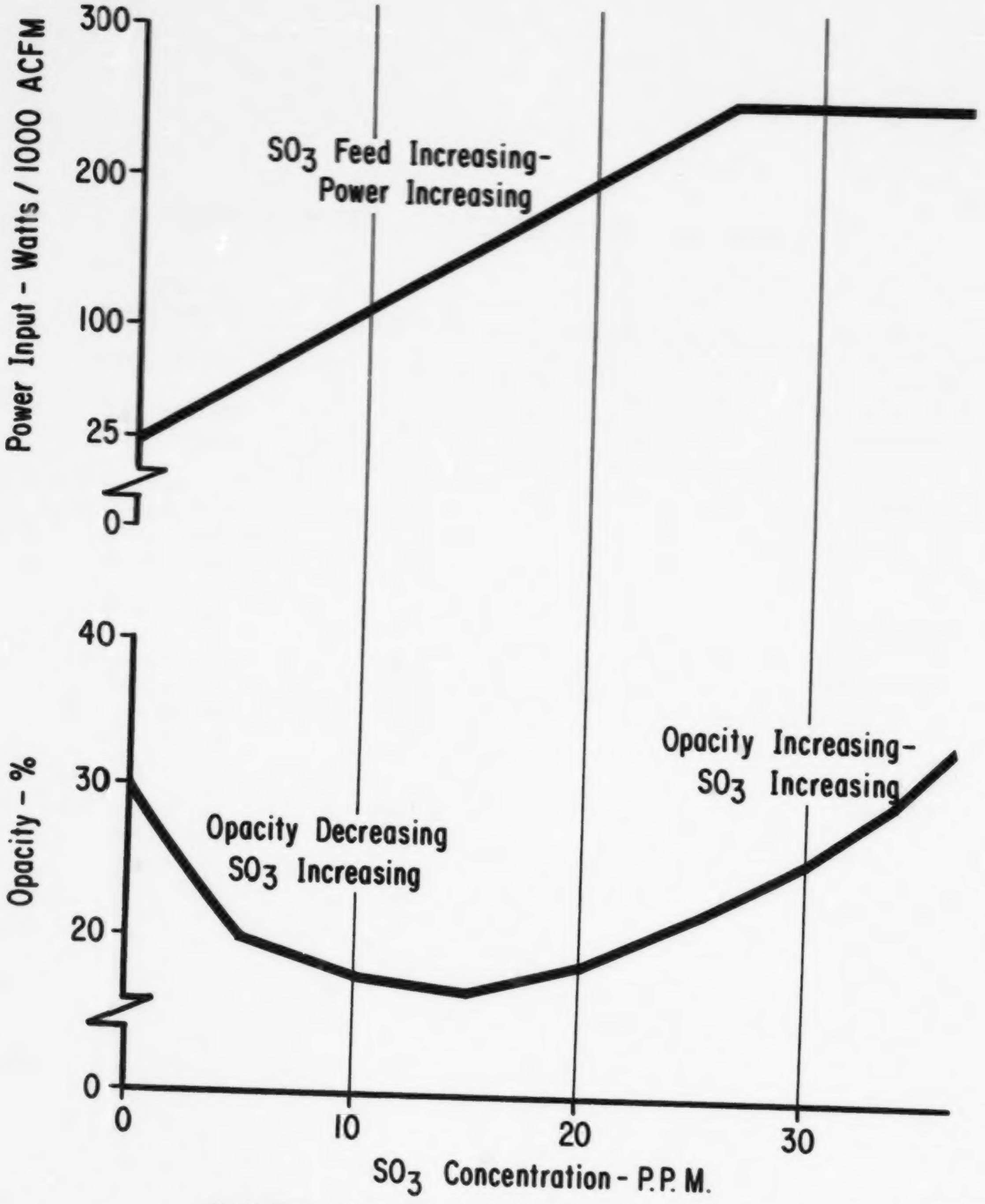
The tests conducted with Big Horn and Decker Coals, which are very similar chemically, indicated the lowest outlet dust loadings were obtained when the SO_3 feed rate was set at six ppm.

The results of these tests verified our earlier findings at State Line Station that maximum precipitator power with flue gas conditioning is not necessarily optimum removal efficiency.

Since the earlier flue gas conditioning units were installed, additional units have been purchased and installed because of fuel changes at the stations. The additional units, as well as those already installed, are shown in Table Two. After the installation of the original flue gas



OPACITY VS SO_3 FEED RATE
Figure 2



POWER INPUT AND OPACITY VS SO_3 FEED
Figure 3

TABLE 2. FLUE GAS CONDITIONING SYSTEMS INSTALLED

STATION	UNIT	MW (NET)	DATE OPERATIONAL
Fisk	19	341	April, 1979
Crawford	7	222	March, 1979
	8	326	March, 1979
Joliet	5*	117	December, 1975
	6	344	December, 1975
	7	537	June, 1976
	8	537	June, 1976
Powerton	5	850	July, 1979
State Line	1*	206	September, 1975
	2*	150	September, 1975
	3	190	December, 1974
	4	318	August, 1975
Waukegan	5*	117	October, 1975
	6	88	October, 1975
	8	358	May, 1976
Will County	4	520	June, 1979

*Units No Longer in Operation

conditioning systems, some of the generating units were retired, however, at the present time, sulfur burner type SO_3 systems are installed on twelve units totaling over 4,600 megawatts.

The new flue gas conditioning systems have been greatly improved over the original units and require very little operator attention or maintenance. The diaphragm type pumps used on the original units have been replaced with positive displacement piston type pumps. They are now properly sized and will produce as little as four ppm SO_3, which will allow conditioning of coals, such as Decker to obtain optimum particulate removal.

Our experience with these systems indicates that they are reliable and greatly improve precipitator performance at a comparatively low investment and operating cost. The sulfur trioxide flue gas conditioning systems have saved Edison several hundred million dollars in capital costs which otherwise would have been required to replace or increase the size of existing precipitators.

The increasing size and cost of precipitators to meet the new source EPA standards has made a combination of flue gas conditioning and subsequently smaller precipitators a viable option. When purchasing new precipitators in the future, the specification will require proposals for a precipitator with and without flue gas conditioning. An economic analysis will then be performed to determine the most cost effective way to meet particulate emission requirements.

THE APPLICATION OF A TUBULAR WET ELECTROSTATIC PRECIPITATOR FOR FINE PARTICULATE CONTROL AND DEMISTING IN AN INTEGRATED FLY ASH AND SO_2 REMOVAL SYSTEM ON COAL-FIRED BOILERS

By: Dr. Even Bakke
Howard P. Willett
Peabody Process System
835 Hope Street
Stamford, CT 06907

ABSTRACT

The development of a combined, tubular, wet electrostatic precipitator (WESP) and vapor condensing heat exchanger mounted in the top section of an SO_2 absorber will be discussed.

Pilot plant data on an integrated fly ash and SO_2 removal system with a variable pressure drop venturi, a high velocity spray tower and the WESP will be presented. Data will show that it is possible to operate with a specific collection area in the WESP of only 20 to 30 sq. ft/1000 ACFM, tube velocities of 16 to 20 ft/sec. overall system pressure drop of 4 to 8 in. W.G. and still have fly ash removal efficiencies in the range from 99.25 up to 99.65% or outlet emissions from 0.015 gr/scfd to 0.006 gr/scfd.

Heat recovery and flue gas reheat options made possible by the WESP/heat exchanger combination will be discussed. Commercial installations of this system on industrial boilers will be reviewed. Initial and annualized costs and space-saving benefits will be presented.

NOTE: Please contact the authors for information regarding this paper.

FIELD EVALUATIONS OF AMMONIUM SULFATE CONDITIONING FOR IMPROVEMENT OF COLD SIDE ELECTROSTATIC PRECIPITATOR PERFORMANCE

By E. C. Landham, Jr.
G. H. Marchant, Jr.
J. P. Gooch

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35255

and

Ralph F. Altman
Electric Power Research Institute
516 Franklin Building
Chattanooga, Tennessee 37411

ABSTRACT

Measurement and analysis of the improvement in cold side electrostatic precipitator performance through the use of ammonium sulfate conditioning agents were conducted at two electric utility generating stations. One plant was burning a low sulfur, high alkalinity Western coal and the other a moderate sulfur, low alkalinity Eastern coal. Comprehensive field tests were performed with and without the agent in use to evaluate the change in performance as well as to determine the mechanisms involved. The measurements conducted included total mass and fractional efficiencies, particle size distributions, rapping emissions, in situ resistivity, ash and flue gas analyses, and voltage-current characteristics of the power supplies. Measurements were made with a proprietary formulation of ammonium sulfate injected on the hot and cold sides of the air heater and with a generic formulation injected on the cold side. The performance of the precipitators was compared with predictions of a theoretical model, and an engineering analysis of the installations was performed.

INTRODUCTION

Electrostatic precipitators (ESPs) are the most widely used particulate control devices in the utility industry due to inherently low energy and maintenance requirements. However, the performance of these devices can be severely limited by high ash resistivity, which causes sparking and back corona, and can also be limited by dust reentrainment during electrode rapping. Operating problems have developed at a number of installations where utilities have changed to low sulfur coals in an effort to comply with SO_x

emission limitations. At some of these installations conditioning of the flue gas or the coal supply with certain chemical compounds has significantly improved ESP performance. Even so, successful application of conditioning agents has not been consistent primarily due to a lack of knowledge of the mechanisms involved. This paper reports the results of studies conducted under the sponsorship of the Electric Power Research Institute (EPRI) at two power plants using ammonium sulfate as a conditioning agent. Ammonium sulfate was chosen for study because: 1) it has the potential for enhancing ESP performance through several different mechanisms, 2) it is a relatively innocous chemical, and 3) it is economical and readily available. Furthermore, it has received fairly widespread usage in full scale plants as an ingredient of one or more proprietary formulations. The studies were designed to: 1) quantify the improvement in performance of the control device due to the use of the agent and, 2) determine the mechanisms by which the agent effected the improvement.

The two power plants included in the research program were the Corette Station of Montana Power Company and Unit 6 of the Gannon Station of the Tampa Electric Company. Both stations use ammonium sulfate for conditioning in a cold side precipitator. At Corette, injection of ammonium sulfate solution is made ahead of the air preheater, where the temperature is high enough to decompose ammonium sulfate into ammonia, sulfur trioxide, and water vapor. At Gannon 6, injection of ammonium sulfate may be made either before or after the air preheater. In the latter event, decomposition of the agent is not expected to be complete.

Conditioning Mechanisms

The mechanisms by which a conditioning agent may improve ESP performance are:

- Reduction of resistivity and/or alteration of the electrical breakdown strength of fly ash allowing more favorable ESP electrical operating conditions.
- Reduction of reentrainment by changing the cohesive properties of fly ash.[1,2]
- Enhancement of the collecting electric field through the formation of a space charge in the region between the discharge and collecting electrodes. This might be accomplished by the formation of a submicron particulate fume of ammonium sulfate.[3]
- Agglomeration or growth of small particles to form larger particles.[4]

Measurements

In order to determine which of these mechanisms were involved in any ESP performance improvement, a test plan was developed which included various measurements conducted both with and without the conditioning agent in use. The measurements were conducted by techniques described by Smith et al.[5]

They included the following:

- Impactor sampling - Determine inlet size distribution for modeling purposes, fine particle collection with and without conditioning, and changes in inlet and outlet size distribution as a result of conditioning agent usage.

- Mass train sampling - Determine particle mass concentrations and overall performance with and without conditioning, quantify rapping reentrainment losses, and collect samples for chemical analysis.

- Resistivity measurements - Determine in situ resistivity of fly ash with and without conditioning.

- Ion mobility measurements - Determine whether the conditioning agent significantly alters the charge carrying characteristics of the flue gas.

- Ultrafine particle measurements - Determine whether the conditioning agent produces a space charge fume of ultrafine particles (at Corette and at Gannon), and (at Corette only) determine the ultrafine particle collection efficiency of the precipitator.

- Chemical analysis - Determine the concentrations of flue gas and fly ash components related to the conditioning agent and monitor coal supply for variations.

- ESP electrical characteristics - Determine the changes in the electrical performance of the ESP caused by the conditioning agent.

CORETTE TEST

Plant Description

The J. E. Corette Station of Montana Power Company has a single 180 MW pulverized coal-fired boiler designed by Combustion Engineering, Inc., to burn a low sulfur subbituminous coal from the Rosebud seam of the Colstrip Mine. The electrostatic precipitator is a small Research Cottrell unit with two electrical fields in the direction of gas flow and a specific collection area of 27.5 $m^2/(m^3/sec)$ (140 $ft^2/1000$ ACFM). A hot air bypass is used to keep the temperature of the ESP below 130°C (270°F) to lower the ash resistivity and improve ESP performance. The chemical injection system was provided by Apollo Technologies, Inc., and introduces the proprietary conditioning agent ahead of the horizontal superheater.

Test Program

Testing at the Corette Station was conducted in three phases: 1) a "conditioning pretest" to obtain some preliminary information on the fate of the injected ammonium sulfate, conducted in August 1979, 2) a conditioning test with comprehensive measurements as outlined previously with the proprietary conditioning agent injected ahead of the air preheater, conducted in

October 1979, and 3) a baseline test with comprehensive measurements without the conditioning agent in use, conducted in November 1979.

Results

The following results have been derived from the laboratory and field investigation concerning the Corette Station.

Collection Efficiency

The collection efficiency of the precipitator, on an overall mass basis, was increased from ~77% to ~98% as a result of the use of the conditioning agent. Table 1 presents overall performance data obtained during the test program. The size-dependent data indicate that the cumulative mass collection efficiency for particles smaller than 2.0 μm diameter increased from 57% to 92% as a result of conditioning agent usage.

Chemical Analyses

The results of chemical analysis of the proprietary agent used at Corette indicate that the primary active constituent of the agent was ammonium sulfate, which represented about 38% of the agent by weight (most of the balance was water). As indicated in subsequent discussion, the test results can be explained by considering the effects of the decomposition products of ammonium sulfate (ammonia and sulfur trioxide) on fly ash resistivity. No effort was made to determine the effect that a low concentration of urea (1.8%), which was also detected in the agent, might have had on precipitator performance, but there was no evidence of a significant effect.

Proximate and ultimate analyses of coal samples collected during the separate tests during August, October, and November 1980, are given in Table 2. These indicate that the coal was reasonably uniform throughout the test series.

Analytical data for the fly ash from the separate tests are given in Table 3. The concentration of the elemental oxides (the first 11 components listed) indicate that the primary differences related to electrical resistivity were in the sodium oxide; the values were approximately 1.0% in August, 0.4% in October, and 0.6% in November. These variations are noted because of the importance of sodium ions as a charge carrier in the precipitated ash.[6,7] The variations are significant in that the conditioning process had to overcome a higher inherent resistivity level during the October conditioning test than that in the August conditioning test or that indicated by the baseline data acquired in November.

The results of determinations of ammonia and sulfur trioxide in the flue gas and on the fly ash during the conditioning tests in August and September are presented in Table 4. These measurements show clear evidence that the ammonium sulfate did decompose into ammonia and sulfur trioxide as expected. Apparently, the use of only two injection nozzles was not sufficient to produce a uniform distribution of the conditioning agent. This is illustrated by the high concentrations of ammonia and sulfur trioxide measured at the air heater inlet port and by the variation in ammonia concentration from port to port at the ESP inlet. A substantial loss of ammonia (and perhaps an equivalent amount of sulfur trioxide) occurred across the air heater, which may be attributed to deposition of ammonium sulfate as a solid deposit on the surfaces of the air heater or to surface-catalyzed oxidation of ammonia to elemental nitrogen and water vapor. Most of the sulfur trioxide was taken up by the alkaline ash whereas most of the ammonia that remained in the gas phase after the air heater was discharged through the stack.

Electrical Resistivity Studies

Measurements of the electrical resistivity of the fly ash in situ were made during each of the field tests with a point-plane resistivity probe by procedures described in another document.[5] In addition, laboratory resistivity measurements were performed to substantiate observations made in the field and to provide information that could be used to interpret the action of the conditioning agent.

Field- and laboratory-measured resistivity values and predicted resistivity values are compared in Figure 1. The field results without conditioning are represented by the upper shaded area and those with conditioning by the lower shaded area. Laboratory results with sulfur trioxide concentrations of 0, 1.8, and 2.5 ppm at a selected temperature (about 140°C) are shown by the solid triangles. Finally, predicted resistivity values through a range in temperature for sulfur trioxide concentrations of 0, 1, and 3 ppm are portrayed by the three curves. The field measurements without conditioning were obtained at sulfur trioxide concentrations below 0.5 ppm; the measurements with conditioning were obtained at an average sulfur trioxide concentration around 1.0 ppm from the ammonium sulfate conditioning agent. It is thus appropriate to compare the baseline field data with the single laboratory data point obtained with no added sulfur trioxide (the uppermost triangle) and the predicted curve for no added sulfur trioxide. The agreement is excellent. It is further appropriate to compare the conditioning test data from the field at about 1 ppm of sulfur trioxide with an interpolated location between the two laboratory data points at 0 and 1.8 ppm (the upper two triangles) and the middle of the three predicted curves (for 1 ppm of sulfur trioxide). Again the agreement is very good.

General observations to be made from Figure 1 are as follows: 1) the resistivity of the ash is highly sensitive to temperature in the operating range of the Corette plant, below 150°C (300°F), and 2) the resistivity is also highly responsive to the presence of even minor concentrations of sulfur trioxide.

Three other laboratory resistivity measurements were conducted on the ash to investigate possible mechanisms by which the ash resistivity might be lowered by a factor of ten as observed with the field measurements. These consisted of:

1. Mixing ammonium sulfate particulate with the ash at a concentration of 1% by weight to simulate co-precipitation of ammonium sulfate in the precipitator.
2. Exposure of the ash to sulfur trioxide followed by exposure to ammonia to attempt to reform ammonium sulfate as an essentially continuous surface deposit.
3. Exposure of the ash to ammonia vapor alone.

In each of these experiments the ash was subjected to concentrations far in excess of those encountered in the field, but none of these techniques produced more than a factor of two change in the resistivity.

In summary, the laboratory studies showed that only sulfur trioxide produced an effect on resistivity of the same magnitude as that observed in the field. In addition, the effect produced by sulfur trioxide was quantitatively comparable with that observed in the field.

Precipitator Electrical Characteristics

The electrical operation of the precipitator power supplies during the test series was consistent with the in situ and laboratory measured values of resistivity for the with- and without-agent conditions. Comparison of the baseline and conditioning test data indicate that the overall useful average precipitator current density increased from 2 to 24 nA/cm^2 when the conditioning agent was used.

The average operating points and voltage-current relationships for the precipitator indicate that the baseline data exhibit severe limitations due to high resistivity, whereas the conditioning agent data sets show that increased values of voltage and current are possible before back corona or sparking is encountered. However, under certain high load, high temperature conditions, the resistivity reduction produced by the conditioning agent was not sufficient to allow the desired level of collection efficiency to be achieved.

Reduction of Reentrainment (Increased Cohesiveness of the Precipitated Ash)

Measurements of ESP collection efficiency with the electrode rappers energized and de-energized indicate that the fraction of emissions attributable to rapping did decrease with conditioning agent usage. However, the amount of emissions due to rapping with the agent in use were not significantly less than those predicted from a correlation developed for ESPs with no conditioning agent employed.[1] These results suggest that the most important mechanism in the reduction of rapping emissions was the improved electrical characteristics of the precipitator, which allowed a greater mass fraction of the dust to be collected in the inlet fields during the with-agent test series. This, in turn, allowed lower mass collection rates in the outlet fields, and thus less dust was collected between raps for possible reentrainment in the outlet fields. Since a precipitator follows an exponential mass collection efficiency relationship with collection area, higher overall collection efficiencies generally result in reduced mass collection rates in outlet fields.

Space Charge Enhancement

Particle concentration measurements with an ultrafine particle sizing system with agent injection on and off provided no evidence of a submicron fume as a result of the ammonium sulfate injection. Similarly, the ESP voltage-current relationships gave no evidence of space charge enhancement resulting from introduction of a submicron particulate.

Ion mobility determinations were made with a wire-pipe corona device inserted in the flue for the with- and without-agent test series. The data from this instrument indicated no significant differences in the mobility of the charge-carrying components of the flue gas as a result of conditioning agent usage. If a less-mobile component of the flue gas were to assume a significantly increased fraction of the charge flux, the result would be a space charge enhancement similar to that described with the introduction of a submicron fume.

Particle Agglomeration

Inlet size distribution data obtained from impactor traverses for the baseline and the conditioning test series show that, within the accuracy of the instrumentation, the conditioning agent does not influence the inlet size distribution over the particle size range resolved by the impactors. Similarly, the ultrafine sizing system detected no significant particle concentration or size distribution changes at the ESP inlet over the particle size range from approximately 0.05 to 0.5 μm diameter.

Performance Analysis

A computer program developed to simulate ESP operation[8,9] was used with the data obtained at Corette as input for the baseline and for the conditioning agent test series to project overall mass efficiency as a function of specific collection area. The results from these simulations are plotted in Figure 2, along with the experimental data obtained with mass trains. The results indicate the mathematical model was reasonably successful in predicting the overall collection efficiencies for both test series, although the baseline efficiency was significantly lower than the value the model predicted. This results from the unusually large reentrainment emissions obtained with a two-stage ESP with poor electrical operating conditions, and from the difficulty of estimating useful electrical conditions when the ESP power supplies are operating with severe sparking or back corona. The correlation used in the model for estimating reentrainment was obtained using data from relatively high efficiency ESPs with several fields in the direction of gas flow.

The significance of these results is illustrated by projecting the measured efficiency point from the with-agent test series to the required value of specific collection area on the curve generated by the model for the baseline electrical conditions. This exercise indicates that, without conditioning, a specific collection area of approximately 375 ft^2/1000 acfm, i.e. an ESP over two and one-half times as big, would be required to give the 97.5% efficiency level obtained with conditioning agent in use. The baseline model projections represent the worst case of high temperature, low sodium, high resistivity conditions observed during the test program.

GANNON 6 TEST

Plant Description

Gannon Unit 6 is a 350 MW pulverized coal-fired Riley Stoker boiler built in 1967. It utilizes a Research-Cottrell cold side precipitator that treats a flue gas volume of 1,350,000 ACFM with a specific collection area of 64.0 $m^2/(m^3/sec)$ (326 ft^2/1000 ACFM). The ESP has four identical chambers each with eight electrical sections in the direction of gas flow.

The gas conditioning system was designed and installed by Apollo Technologies, Inc. It is similar to that used at the Corette Station. It can be used for injection of an ammonium sulfate solution prior to either the air preheater or the ESP (hot side or cold side injection). It was operated in both modes during the investigation discussed in this report. Its normal mode of operation is now cold side injection; originally the normal mode was hot side injection as at Corette.

Test Program

Testing at the Gannon Station consisted of four phases: 1) a baseline test with no conditioning agent in use, conducted in December 1979, 2) a "cold side proprietary agent test", in which measurements were performed in January 1980 with the normal plant procedure of injecting the proprietary conditioning agent downstream of the air preheater, 3) a "cold side generic agent test", in which a solution of 36% ammonium sulfate in water was injected downstream of the air preheater, also in January 1980, and 4) a "hot side proprietary agent test" in which the proprietary agent was injected ahead of the air preheater. This last phase was performed during the period January 30 - February 1, 1980. As a result of T-R set outages on one side of the precipitator, most of the measurements were obtained across only one of the four chambers (Chamber 4) during all four phases.

Results

The results of experiments performed at Gannon Unit 6 and supporting experiments performed in the laboratory are described below.

Collection Efficiency

Normal precipitator mass collection efficiency data were obtained during three of the four test phases using EPA Method 17 mass concentration measurements across Chamber 4 of the precipitator. In the fourth series of tests, which were conducted with proprietary agent injected ahead of the air preheater, only the "rap/no-rap" procedure employing mass train measurements was performed. The purpose of this procedure was to determine whether hot side injection of ammonium sulfate resulted in significant differences in reentrainment emissions when compared with cold side injection. Mass efficiency data are shown in Table 5, with data obtained by the rap/no-rap method shown in parentheses.

It is apparent from these data that the precipitator was performing at a high level of collection efficiency even when the conditioning agent was not in use. However, there is considerable evidence from resistivity measurements and T-R set data that the baseline measurements were unfortunately not representative of normal baseline conditions. This problem will be considered further in the subsequent discussion of conditioning mechanisms. Even though the baseline collection efficiency is considered to be higher than normal, the efficiency data consistently show that reduction in penetration, or increases in collection efficiency, occurred as a result of agent usage.

The mass penetration of particles smaller than 2.0 μm diameter was reduced by 40 - 60% as a result of the injection of ammonium sulfate.

Chemical Analyses

Two conditioning agents were used in the studies at Gannon Unit 6. One was a proprietary agent supplied to Tampa Electric Company by Apollo Technologies, Inc. The second agent was a "generic" agent--an aqueous solution of ammonium sulfate purchased by Tampa Electric from another chemical supplier. The analyses of the two agents confirmed that ammonium sulfate was the predominant component of each. The data also show that urea was present at a low concentration in the proprietary agent but absent from the generic formulation.

The results of coal analyses (Table 6) indicated that no unacceptable variation occurred during the different phases of testing at Gannon Unit 6. Comparison of the coal properties with those of the coal burned at Corette reveal that the coal at Gannon was of higher rank and contained a higher level of sulfur.

Analytical data for samples of hopper ash obtained during each of the field tests at Gannon are given in Table 7. The major difference between this ash and that encountered at Corette is the much lower alkalinity of the Gannon ash (as indicated by the calcium oxide content). The uptake of ammonia by the ash was increased significantly due to this reduced alkalinity.

The data in Table 8 show that significant concentrations of ammonia and sulfur trioxide were found in the gas phase at the inlet of the precipitator, indicating a substantial degree of thermal decomposition of ammonium sulfate even with cold side injection and a significant persistence of the gaseous decomposition products at the reduced temperature following hot side injection.

Comparison of the concentrations of ammonia and sulfur trioxide in the gas phase with those in the fly ash shows that a substantial fraction of each substance occurred in each phase. Thus, the markedly preferential uptake of sulfur trioxide over that of ammonia that was observed at Corette was not observed at Gannon. The difference in behavior of the two ashes in this regard is attributed to the lower alkalinity of the Gannon ash, which makes this ash less hostile to the uptake of ammonia.

Electrical Resistivity Studies

Measurements of the electrical resistivity of fly ash were made for Gannon Unit 6, as at Corette, in both the field and the laboratory. Also, predicted resistivities were compared with the field- and laboratory-measured values. The general purposes of this work were to quantitate the effect of the conditioning agent on resistivity, to elucidate the mechanism of resistivity attenuation (through the action of undecomposed ammonium sulfate or the individual decomposition products), and to test the agreement between measured and predicted values.

Figure 3 includes a presentation of field-measured resistivity values. The two shaded areas and the two data points therein show the regions occupied by the data and the averages calculated from the data for tests with and without conditioning. The upper area is for the baseline test; the lower area is for all three conditioning tests and reveals a reduction of resistivity of almost one order of magnitude as the result of conditioning.

Figure 3 also presents laboratory data obtained at three concentrations of sulfur trioxide (0, 2, and 6 ppm). Comparison of the baseline field data with the laboratory data shows reasonable agreement at a laboratory concentration of zero sulfur trioxide. Comparison indicates, further, that the field data obtained with conditioning would agree with laboratory data at a concentration between the two experimental values of 2 and 6 ppm. Field concentrations for sulfur trioxide were (1) less than 1 ppm in the baseline test (determined at the inlet of Chamber 1) and (2) 0.8 to 2.4 ppm in the three conditioning tests (determined at the inlet of Chamber 4). Thus, the overall agreement between the field and laboratory data is reasonably satisfactory and indicates that the sulfur trioxide produced by thermal decomposition of the ammonium sulfate is the probable explanation of the reduction in resistivity observed during the field conditioning tests. However, since some differences existed between the Corette and Gannon ashes, the experiments to evaluate the effects of co-precipitation of ammonium sulfate and treatment by gaseous ammonia were repeated. The results showed, as at Corette, less than a factor of two change in resistivity due to these mechanisms.

In conclusion, therefore, the apparent mechanism of resistivity attenuation is the uptake by ash of sulfur trioxide resulting from the thermal decomposition of ammonium sulfate.

Precipitator Electrical Characteristics

Electrical characteristics of the precipitator power supplies showed evidence of the attenuation of electrical resistivity that was revealed by both the field- and laboratory-measured values discussed above. Secondary voltages and currents of the power supplies were recorded daily during each of the test phases, and total power inputs were calculated from these data. Average daily power inputs to the east side of the Gannon Unit 6 precipitator (serving Chambers 3 and 4) during each phase of the testing show an average of 158 KW during the baseline test versus 254 KW for the conditioning tests.

There was no evidence of back corona without conditioning, but the current density attainable without sparking was enhanced by conditioning. The absence of back corona in the baseline test was confirmed by high voltage wave-form photographs.

There was evidence of a slow degradation of the ESP performance during the baseline test. Although the average total power input to the eight electrical sections was about 158 KW during nine days of measurements, there was a gradual decrease from about 200 KW on the first day to about 100 KW on the ninth day. The favorable subsequent effect of conditioning was thus greater than that indicated by the average value from the baseline test. The gradual degradation of the ESP during the baseline test may have been caused by a delay in elimination of residual effects of ammonium sulfate that had accumulated during prior operation with conditioning, perhaps a gradual evolution of sulfur trioxide from a deposit of ammonium sulfate in the duct leading to the ESP.

Reduction of Reentrainment (Increased Cohesiveness of the Precipitated Ash)

Tests to compare emissions under rap and no-rap conditions were conducted at Gannon Unit 6 during three of the test series: baseline, generic agent with cold side injection, and proprietary agent with hot side injection (similar results for cold side injection of the proprietary and generic agents was expected). Rapping emissions were quantified by two measurement systems--Method 17 mass trains and a Large Particle Sizing System (LPSS) designed by this Institute to determine real-time particle concentrations in five size ranges.

The results obtained with the Method 17 mass trains reveal that both rap and no-rap emissions were reduced on an absolute basis with conditioning in progress. The data were in quantitative agreement with predictions made on the basis of no assumed change in dust cohesiveness. The inference, therefore, is that no large change in cohesiveness occurred.

The LPSS data were in agreement with the Method 17 data. The primary additional information provided by the LPSS was an indication that, as expected, most of the rapping emissions were of the larger particles, specifically those larger than 3 μm.

Space Charge Enhancement

Three types of data provided the basis for deciding whether or not the use of ammonium sulfate conditioning produced a fine fume that could have enhanced space charge and thus improved electrical conditions. First was direct measurement of concentrations of ultrafine particles (from about 0.01 to 2.0 μm). Data obtained in the baseline test fell between results of two conditioning tests, and cumulative concentrations were all within a factor of two of each other; thus, no evidence of a fine fume during conditioning was obtained. Second were the voltage-current density curves of the precipitator transformer-rectifier sets; current density was shifted to higher values by conditioning, giving evidence that resistivity attenuation overwhelmed any contrary shift associated with space charge enhancement. Third were determinations of ion mobilities *without conditioning* at Gannon Unit 6 and with conditioning at Gannon Unit 5 (equipment problems prevented measurements at Unit 6 with conditioning); mobility values for both circumstances were within the normal range and gave no evidence of the suppression associated with fine particles.

Particle Agglomeration

Particle size distributions at the precipitator inlet with and without conditioning, as obtained with impactors and the ultrafine particle sizing system give no indication of particle growth as the result of conditioning.

Performance Analysis

Figure 4 gives the result of computer model simulation of the Chamber 4 precipitator with three electrical data sets: 1) those observed during baseline conditions, 2) those observed with cold side injection of the generic conditioning agent, and 3) a current density of 5 nA/cm^2, which would represent the expected allowable current density if the in situ resistivity increased by a factor of four over the measured values observed at the entrance to Chamber 4 during the baseline test series. This factor of four increases in resistivity would represent the expected average value of resistivity across the inlet to the precipitator in the absence of any residual effects from the conditioning agent.

These computer simulations illustrate how the performance of the unit can become marginal with electrical conditions consistent with the expected average values of baseline resistivity. The loss of one equivalent electrical section would lower the efficiency to a range in which consistent compliance with the local emission standard of 0.1 $lb/10^6$ Btu would become doubtful.

ECONOMIC ANALYSIS

At both the Corette and Gannon installation, the major cost element associated with use of the conditioning agent is the purchase cost of the chemical compounds. At Corette, the cost of the conditioning agent is 0.143 mills/kWh, and at Gannon, the cost is 0.08 mills/kWh.

At both installations, the use of the conditioning agent is cheaper, on the basis of levelized annual costs, than the alternative option of adding precipitator plate area to achieve the levels of particulate control which the conditioning agent allowed to be obtained with the existing plate area. The plate area requirements without the use of conditioning agent were estimated using the EPA-SoRI mathematical model of electrostatic precipitation.

CONCLUSIONS

The following conclusions about the use of ammonium sulfate to condition cold side precipitators can be drawn from the results discussed in this report.

- The active ingredient of both the proprietary and generic conditioning agents was ammonium sulfate. A trace of urea occurred in the proprietary agent, but apparently did not affect precipitator performance.

- Decomposition of the ammonium sulfate to ammonia and sulfur trioxide occurred with both hot side and cold side injection. However, decomposition was less complete at the lower injection temperature and approximated the degree predicted from thermodynamic data.

- Addition of ammonium sulfate improved the collection efficiency of the two precipitators tested on both a total mass and fine particle basis. The performance improvements ranged from 20% to 90% reduction in mass penetration of the precipitator.

- The primary mechanism by which ESP performance was improved was a decrease in fly ash resistivity which allowed the precipitator to operate at higher power levels. The major part of the reductions in resistivity can be attributed to the effect of sulfur trioxide alone.

- The conditioning agent does not significantly change particle size for particle sizes larger than 0.05 μm diameter. Thus, it gives no evidence of conditioning through the mechanisms of fly ash agglomeration or production of an ultrafine fume.

- The reduction in rapping emissions was primarily due to improved collection in the inlet fields and not to a large change in the cohesive properties of the dust.

- The use of ammonium sulfate as a conditioning agent can be economically favorable method of improving performance in comparison to additions of precipitator plate area. However, operational problems associated with its use can include air heater pluggage with hot side injection and duct buildups, if distribution is inadequate, with cold side injection. Moreover, under certain operating conditions, the resistivity reduction achieved by ammonium sulfate conditioning may be insufficient.

ACKNOWLEDGMENTS

Officials of Montana Power Company and Tampa Electric Company were most cooperative in providing field test facilities and adjusting normal plant operating procedures to accomodate the needs of this research program. Assistance by Carlton Grimm and Fred Walter of Montana Power and James L. Hudson, Jr., of Tampa Electric was especially noteworthy.

ENDNOTES

1. J. P. Gooch and G. H. Marchant, "Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies", Report EPRI FP-792, Volume 3, Electric Power Research Institute, Palo Alto, California 1978.

2. J. Dalmon and D. Tidy, Atmos. Environ. 6, 81 (1972).

3. E. B. Dismukes, "Conditioning of Fly Ash with Sulfur Trioxide and Ammonia," *Report EPA-600/2-75-015 (TVA-F75 PRS-5)*, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina (Tennessee Valley Authority, Chattanooga, Tennessee), 1975.

4. E. C. Potter and C. A. J. Paulson, Chem. Ind. 1974, 532.

5. W. B. Smith, K. M. Cushing, and J. D. McCain, "Procedures Manual for ESP Evaluation," Report EPA-600/7-77/059, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1977.

6. R. E. Bickelhaupt, "Influence of Fly Ash Compositional Factors on Electrical Volume Resistivity," Report EPA-600/2-75/074, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1974.

7. R. E. Bickelhaupt, "Effect of Chemical Composition on Surface Resistivity of Fly Ash," Report EPA-600/2-75/017, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1975.

8. J. R. McDonald, "A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I, Modeling and Programming," Report EPA-600/7-78-111a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1978.

9. J. R. McDonald, "A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume II, User Manual," Report EPA-600/7-78-111b, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1978.

Table 1

SUMMARY OF METHOD 17 AND CONDITIONING AGENT DATA FOR THE CORETTE PLANT

Parameters	Test Series: Baseline	Test Series: Conditioning
Average electrical conditions[a]		
Voltage, kV	30	47
Current density, nA/cm^2	2	24
Precipitator		
Efficiency, %	77.30 (69.46)	97.50 (97.13)[b]
SCA, ft^2/1000 acfm	147	143
Outlet emissions, lb/10^6 Btu		
Total	1.78	0.13
<2 µm	0.12	0.025
Conditioning agent		
Addition rate, gal/ton coal	0	0.096
Temperature of addition, °C	-	540-620
°F	-	1,000-1,150

---

a. Estimated useful voltage and current from voltage-current curves.

b. Data in parenthesis are from rap/no-rap measurements.

Table 2

ANALYSIS OF COAL FROM CORETTE[a]

Parameter	August conditioning pretest	October conditioning test	November baseline test
Proximate analysis			
Number of samples	7	17	9
% Moisture	11.66 ± 1.74	12.05 ± 1.56	11.68 ± 1.29
% Ash	11.04 ± 0.52	10.61 ± 0.43	10.68 ± 0.39
% Volatile	34.61 ± 0.63	33.04 ± 0.79	33.65 ± 0.56
% Fixed carbon	42.69 ± 1.00	42.60 ± 0.87	43.99 ± 0.91
Btu/lb	10,172 ± 236	10,079 ± 200	10,206 ± 154
% Sulfur	1.07 ± 0.11	0.71 ± 0.10	0.74 ± 0.03
Ultimate analysis[b]			
Number of samples	-	3	3
% Moisture	-	13.34 ± 0.74	11.31 ± 0.77
% Carbon	-	58.56 ± 0.72	59.61 ± 0.48
% Hydrogen	-	3.94 ± 0.06	3.95 ± 0.05
% Nitrogen	-	1.03 ± 0.10	1.11 ± 0.05
% Chlorine	-	0.10 ± 0.01	0.03 ± 0.01
% Sulfur	-	0.71 ± 0.08	0.72 ± 0.03
% Ash	-	10.37 ± 0.36	10.64 ± 0.32
% Oxygen	-	11.96 ± 0.18	12.63 ± 0.68

---

a. The data given are averages for the numbers of samples indicated plus the standard deviations from the averages.

b. Not performed for the August pretest.

Table 3.

ANALYSIS OF FLY ASH FROM CORETTE

Component[a]	August conditioning pretest[b]	October conditioning test[c]	November baseline test[c]
Li_2O	0.04	0.03	0.04
Na_2O	0.99	0.38	0.60
K_2O	0.67	0.55	0.37
MgO	3.4	5.0	5.6
CaO	16.2	20.7	19.0
Al_2O_3	23.3	21.7	21.4
Fe_2O_3	5.9	4.6	6.2
SiO_2	44.3	41.8	42.2
TiO_2	1.8	2.1	1.2
P_2O_5	0.4	0.3	0.4
SO_3	1.1	1.1	1.4
Total	98.10	98.26	98.41
NH_3	0.010	0.004	0.0001
SO_4^{-2}	0.90	0.70	0.60

---

a. The first 11 components were determined after the sample had been ignited. The last 2 components were determined prior to sample ignition by extracting soluble NH_3 and SO_4^{-2} with water.

b. For a sample collected in the mass train at the ESP inlet.

c. For a proportionate blend of individual samples collected from the ESP inlet and outlet hoppers.

Table 4

COMPARISON OF OBSERVED AMMONIA AND SULFUR TRIOXIDE CONCENTRATIONS IN FLUE GAS AND FLY ASH WITH INJECTED CONCENTRATIONS AT CORETTE

Date of test	Injected Concn, ppm NH_3	Injected Concn, ppm SO_3	Sampling Location	Port No.	Average Observed Concn, ppm: Gas Phase NH_3	Gas Phase SO_3	Fly Ash NH_3	Fly Ash SO_3
Aug.	6.8	3.4	AH Inlet	-	11.3	4.5	0.035	26
			ESP Inlet	2	2.5	<0.5	0.73	12
				3	1.2	<0.5		
				5	1.6	-		
				8	3.4	<0.5		
				10	4.2	-		
			ESP Outlet	-	-	-	0.21	-
Oct.	7.4	3.7	AH Inlet	-	13.1	1.3	0.085	18
			ESP Inlet	1	1.3	-	0.33	12
				2	1.2	0.5		
				5	1.7	-		
				7	-	1.0		
				9	4.0	-		
				10	3.9	-		
			ESP Outlet	-	-	0.7	0.018	0.95
			Stack	-	2.7	<0.5	-	-

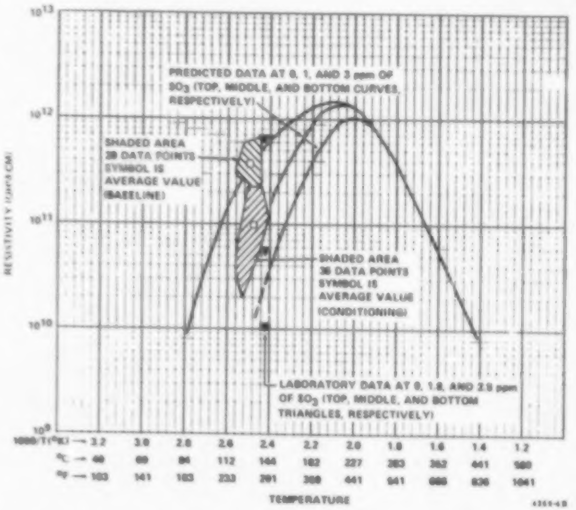


Figure 1. Field, laboratory, and predicted resistivity values for Corette.

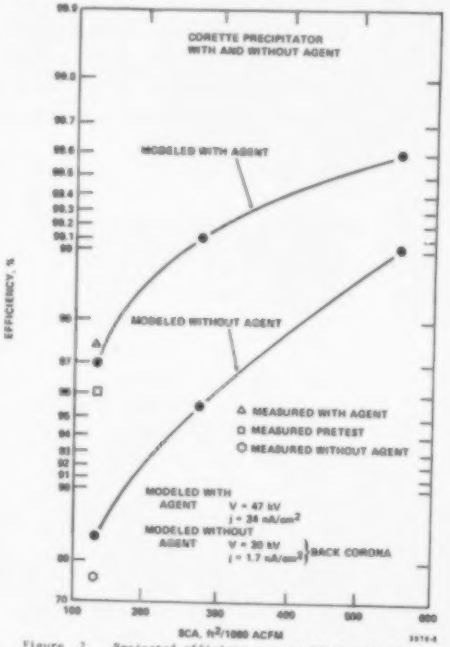


Figure 2. Projected efficiency versus SCA for the Corette precipitator.

Table 5

SUMMARY OF METHOD 17 AND CONDITIONING AGENT
DATA FOR GANNON UNIT 6

Parameters	Test Series Baseline	Conditioning[a] Pr/CS	Ge/CS	Pr/HS
Average electrical conditions[b]				
Voltage, kV	38	40	39	40
Current density, nA/cm^2	20	35	31	29
Precipitator				
Efficiency, %	99.90 (99.73)[d]	99.96 (-[c])	99.92 (99.91)[d]	[c] (99.84)[d]
SCA, ft^2/1000 acfm	332	342	333	335
Outlet emissions, lb/10^6 Btu				
Total	0.006	0.002	0.006	(0.008)[d]
<2 µm	0.001	0.0006	0.0004	-
Conditioning agent				
Addition rate, gal/ton coal	0	0.182	0.189	0.159
Temperature of addition, °C	-	179	175	ca 540
°F	-	355	347	ca 1,1000

---

a. Pr/CS = proprietary agent with cold-side injection.
Ge/CS = generic agent with cold-side injection.
Pr/HS = proprietary agent with hot-side injection.

b. Estimated useful voltage and current from voltage-current curves.

c. No result is available.

d. Data in parenthesis are from rap/no-rap measurements.

Table 6.

ANALYSIS OF COAL FROM GANNON UNIT 6

Parameter	Baseline test	Conditioning tests[a] Pr/CS	Ge/CS	Pr/HS
Proximate analysis				
Number of samples	8	3	5	3
% Moisture	8.13	8.51	8.48	7.96
% Ash	10.24	9.90	9.71	9.01
% Volatile	31.84	31.87	31.82	31.93
% Fixed carbon	49.79	49.72	49.99	51.10
Btu/lb	12,033	12,036	12,039	12,277
% Sulfur	1.14	1.08	1.10	1.19
Ultimate analysis				
Number of samples	3	2	2	2
% Moisture	8.73	8.14	8.76	7.67
% Carbon	67.90	68.60	67.40	69.29
% Hydrogen	4.31	4.16	4.28	4.69
% Nitrogen	1.47	1.52	1.44	1.50
% Chlorine	0.15	0.18	0.14	0.13
% Sulfur	1.15	1.10	1.14	1.21
% Ash	10.19	10.05	9.94	9.04
% Oxygen	6.14	6.25	6.91	6.48

Table 7.

ANALYSIS OF FLY ASH FROM GANNON[a]

Component[b]	Baseline test	Conditioning tests[c] Pr/CS	Ge/CS	Pr/HS
Li_2O	0.01	0.01	0.01	0.01
Na_2O	0.68	0.69	0.63	0.63
K_2O	3.5	4.3	4.2	3.9
MgO	2.0	1.9	1.8	1.7
CaO	2.0	2.0	1.8	2.0
Al_2O_3	23.6	25.0	23.3	23.5
Fe_2O_3	13.6	13.4	13.4	13.8
SiO_2	51.6	48.7	48.0	53.7
TiO_2	1.1	1.3	1.3	1.1
P_2O_5	0.29	0.45	0.34	0.20
SO_3	0.30	0.50	0.90	0.40
Total	98.66	98.25	95.68	100.94
NH_3	0.003	0.050	0.088	0.046
SO_4^{-2}	0.51	1.00	0.99	1.00

a. Computed for proportionate blends of inlet and outlet hopper samples.

b. The first 11 components were determined after the sample had been ignited. The last 2 components were determined prior to sample ignition by extracting soluble NH_3 and SO_4^{-2} with water.

c. The abbreviation for each type of conditioning test is given in Table 10.

Table 8

COMPARISON OF AMMONIA AND SULFUR TRIOXIDE
CONCENTRATIONS IN FLUE GAS AND FLY ASH
WITH INJECTED CONCENTRATIONS AT GANNON

Type of Test[a]	Average Injected Concn, ppm NH_3	SO_3	Sampling Location	Average Observed Concn, ppm Gas Phase NH_3	SO_3	Fly Ash NH_3	SO_3
Pr/CS	12.2	6.1	ESP Inlet	3.6	2.4	4.5	2.8[b]
			ESP Outlet	0.2	0.9	0.1	<1.0[c]
Ge/CS	12.8	6.4	ESP Inlet	2.7	1.2	7.7	6.6[b]
			ESP Outlet	0.2	1.9	0.1	<1.7[c]
Pr/HS	10.6	5.3	ESP Inlet	2.6	0.8	7.3	2.9[b]
			ESP Outlet	0.3	0.6	0.1	<1.0[c]

a. See Table 5 for definition of abbreviations.

b. Calculated as the increment over the SO_3 equivalent in baseline ash. Based on samples collected from the flue gas ducts in mass trains, but in reasonable agreement with data for hopper samples (Table 4-9).

c. Maximum value assuming all the particulate at the ESP outlet was SO_4^{-2}.

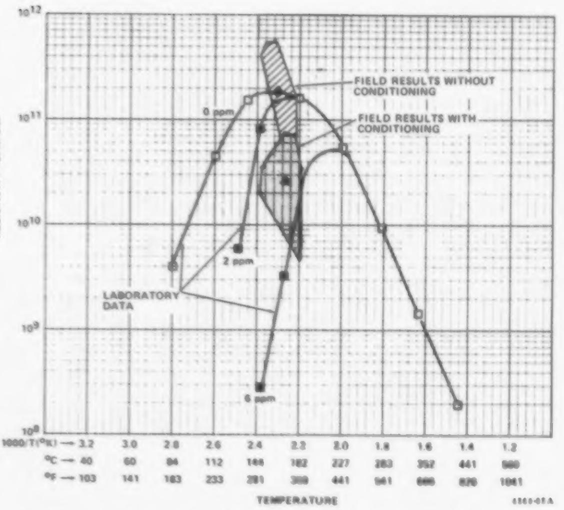


Figure 3. Field and laboratory resistivity values for conditioning tests at Gannon.

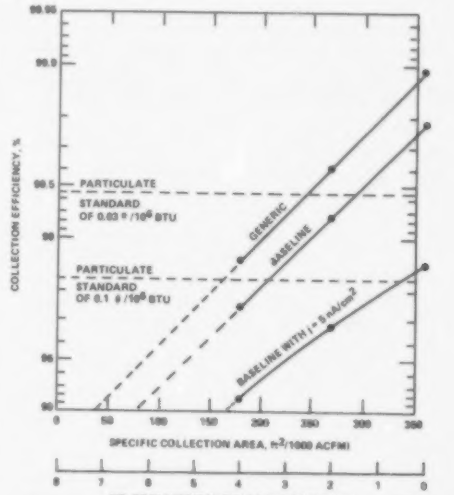


Figure 4. Collection efficiency as a function of SCA or number of fields out of service at Gannon Unit 6. (Actual SCA values ranged from 332 to 342 ft^2/1000 acfm during the separate field tests.)

EVALUATION OF PERFORMANCE ENHANCEMENT OBTAINED WITH PULSE ENERGIZATION SYSTEMS ON A HOT-SIDE ELECTROSTATIC PRECIPITATOR

By Walter Piulle
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94303

L. E. Sparks
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

and

G. H. Marchant, Jr.
J. P. Gooch

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35255

ABSTRACT

Two pulse energization systems of differing design were temporarily installed on separate chambers of a hot-side electrostatic precipitator. Measurements of overall and size dependent collection efficiency were performed using conventional and pulse energization for transformer-rectifier sets on each of the two separate chambers. The enhancement in performance resulting from the use of pulse energization was evaluated on an overall mass and on a particle-size-dependent basis. The results obtained from the full-scale installation are compared with results obtained in a pilot precipitator at EPA's Industrial Environmental Research Laboratory, Research Triangle Park, N.C. The precipitator was performing below design values without the use of sodium conditioning and had experienced a pattern of performance deterioration with accumulated time of operation following plant outages during which the precipitator was cleaned by water washing. Sodium conditioning is normally used to maintain desired levels of performance.

INTRODUCTION

Developments within the electronic industry during the past decade have resulted in the promotion of the concept of pulse energization for improvement of ESP performance. Pulse energization was investigated by H. J. White in the late 1940's and early 1950's but, due to the limitations of the then available equipment, the concept was not pursued. Pulse energization basically involves superimposing high voltage pulses on top of the normal precipitation voltage waveform. Several ESP manufacturers in the U.S. and abroad are now offering pulse energization systems on a commercial scale.

Advantages claimed for pulse energization in comparison with conventional DC energization include: 1) higher peak voltage without sparking; 2) more controllable corona current; 3) more uniformly distributed corona discharges; and 4) higher input power.

Two pulse energization systems of differing design were temporarily installed on separate chambers of the hot-side ESP at the Lansing Smith generating station of Gulf Power Company. Side A of the ESP was equipped with a pulsing system supplied by Buell Envirotech, and side B was equipped with a pulsing system supplied by Research-Cottrell, Inc. A research program was sponsored by the Electric Power Research Institute, the U.S. Environmental Protection Agency, and Southern Company Services, Inc. for the purpose of evaluating the effectiveness of pulse energization as a means of improving hot-side ESP performance. This paper gives preliminary results obtained from the evaluation program.

BACKGROUND

In 1977, hot-side ESP's were retrofitted on both units at Plant Lansing Smith to allow the plant to meet environmental regulations when they began firing low-sulfur, low-sodium South African coal. The units initially passed normal compliance tests, but performance deficiency problems appeared in 1978. A number of potential remedial approaches, such as power-off rapping, the use of improved transformer-rectifier (T-R) set controls, reversible-polarity T-R sets, ammonia conditioning, ESP washdowns, and sodium conditioning, were attempted. With the exception of ESP washdowns and sodium conditioning, these procedures did not produce the desired level of ESP performance. Each ESP washdown did improve performance, but ESP performance degraded over a period of from 1 to 2 months until it reached unacceptable levels. An outage would then be required to perform another washdown. In early 1980, a research program conducted by Southern Research Institute, under the sponsorship of the Electric Power Research Institute, the Environmental Protection Agency, and the Southern Company Services, Inc., was begun to evaluate sodium conditioning as a potential solution to the problem. Unit 2 at the Lansing Smith Station (rated at 196 MW) had been operating since May 1980 (7 months) with sodium conditioning, except for the 8 day period at the beginning of the evaluation period for the pulsers, without an ESP washdown, with acceptable performance levels.

TEST PLAN

The initial evaluation program called for data to be obtained from each chamber of the Unit 2 ESP with each vendor's pulsing system operational and with no sodium conditioning of the coal supply. These data were to be compared with baseline data taken previously on Lansing Smith Unit 2 when the ESP was in a degraded condition without sodium conditioning. A test series was also planned which consisted of ESP efficiency measurements for each chamber to determine the effectiveness of pulse energization for sustaining desired levels of performance for an extended operating period (2 to 3 months). Although it was desirable to arrange the pulsing systems for each chamber in an identical configuration for evaluation purposes, equipment limitations prevented this goal from being accomplished. Figure 1 (top) gives the original electrical sectionalization of the ESP, and the electrical sectionalization and areas pulsed during the pulse energization test program (bottom). As the diagram indicates, the outlet half of the plate area was pulsed on the A side, whereas the inlet 80% of the plate area was pulsed on the B side.

The test program began at Plant Lansing Smith the first week of November, 1980, with no sodium conditioning of the coal supply. After the unit had operated for 7 days without sodium conditioning, ESP performance had degraded to the point that, even with both pulsers operational, compliance with local emission codes could not be maintained unless unit load was reduced, or unless the sodium conditioning system was placed back in service. Plant management then ordered the activation of the sodium conditioning system to increase the sodium oxide content in the fly ash. From previous conditioning tests, the level required for acceptable performance was determined to be $\sim$1%. On November 17, the sodium oxide content in the fly ash was $\sim$1%, and testing was performed with impactors on the B side ESP with and without pulser operation. At this level of sodium addition, ESP performance was relatively high ($\sim$13% plume opacity), and the effect of the B side pulser on outlet emissions was difficult to determine. A tube leak necessitated the unit to be off-line on November 18, 1980. After start-up, plant management agreed to lower the sodium addition rate in order to degrade the electrical operating conditions so that the effects of the pulsers could be discerned at a lower ESP performance level. The sodium oxide content of the fly ash was reduced to approximately 0.7%. At this level of sodium conditioning, stack emissions were at a level which could be tolerated, and effects of the pulse energization systems were discernible. As a result of the inability of the ESP to maintain compliance without sodium conditioning, the evaluation of the capability of pulsing to maintain a given level of performance for an extended period was not conducted.

RESULTS

Averaged results from the Method 17 mass sampling system are presented in Table 1. Table 2 summarizes results from a previously conducted sodium conditioning test series for comparison. Coal and ash analyses are given in Tables 3 and 4. For reasons previously discussed, only a limited amount of data were obtained with no sodium addition to the coal supply. The results obtained indicate that penetration decreased from 3.33% to 1.57% on the B side, and from 3.76% to 1.68% on the A side as a result of pulse energization with no sodium addition. However, the increase in performance on the A side during the November 13, 1980, test appears to have been associated at least in part with a coal composition change due to sodium sulfate contamination of the coal supply. Chemical analysis of fly ash obtained on November 13, 1980, gave an Na_2O content of 0.41% in the fly ash, whereas the normal baseline Na_2O content of ash from the South African coal is 0.32%.

For the test condition of $\sim$0.7% Na_2O in the fly ash, the averaged mass train results indicate that penetration decreased from an average of 1.67% to

0.93% on the A side, and from 1.76% to 0.58% on the B side as a result of pulse energization. Individual efficiencies from which these average values were obtained are given in Table 1.

Total mass loadings obtained from traverses of the inlet and outlet sampling ports with impactors are given in Table 5. Since it is necessary to maintain constant flow through an impactor to obtain size resolution, isokinetic traverses are not possible. However, traverses were made at a flow rate isokinetic to the average gas velocity in the duct at the sampling location. The results from these measurements indicate, as stated previously, no significant change in performance due to pulse energization on the B side (0.80% vs. 0.71% penetration) with sodium conditioning at a level equivalent to ∿1% Na_2O in the fly ash. Side A was not tested due to pulser equipment failure. For the ∿0.7% Na_2O addition level, the impactor data indicate penetration decreased from 2.01% to 1.25% on the A side, and from 1.82% to 1.17% on the B side as a result of pulse energization.

Figure 2 gives efficiency as a function of particle diameter for the A side of the ESP with and without pulsing at approximately 0.7% Na_2O level. Also shown for comparison are analogous data obtained during the sodium condition test series with sodium at approximately the 1% Na_2O level. The data indicate that significant improvements in collection efficiency as a result of pulse energization were detected only for particle diameters larger than about 2.0 μm. Size dependent efficiency data for the B side are presented in Figure 3. These data indicate that, up to about 1.5 μm particle diameter, efficiency changes due to pulsing are either marginal or not detectable by the impactor sampling systems. For particle diameters larger than 1.5 μm, significant collection efficiency improvement due to pulsing is indicated. Size-dependent cumulative emission data for the two pulsing systems are given in Figures 4 and 5; sodium conditioning test data are shown for comparison. These cumulative emission data also illustrate that the performance changes due to pulsing are observed primarily for particles larger than 1.5 to 2.0 μm diameter.

In addition to the impactor sampling system, an extractive sampling system (which employs a diluter, an electrical aerosol analyzer, and an optical particle counter) was used at the outlet of each chamber. This system is described in detail elsewhere.[1] The system samples at a single point, and uses electrical mobility and the optical properties of the particles as a basis for obtaining particle size distribution data. It also enabled pulser-on/pulser-off comparison on a real time basis. Outlet particle concentrations were obtained with pulsing systems on and off, and the observed changes due to pulse energization were reported as a percent reduction at a specified particle diameter. These results are displayed in Table 6. The percent reductions shown approach the "noise level" of this type of instrumentation. These results are interpreted as supporting the conclusion, derived from the impactor data, that large changes in collection efficiency were not achieved by the pulsing systems in the fine particle size bands.

Figure 6 presents data obtained at EPA's IERL-RTP laboratories in a pilot unit with and without pulse energization. These results are discussed in detail elsewhere,[2] and were obtained under conditions which were significantly different (cold-side conditions with resuspended ash) from those encountered at Lansing Smith. However, it is interesting to note that these data also indicate significant performance enhancements due to pulsing for particle diameters larger than about 1.5 μm.

A modified Millikan cell was used at the outlet of each chamber to obtain charge as a function of particle diameter using a technique described by McDonald.[3] The purpose of these measurements was to obtain insight into the mechanisms through which pulsing influences ESP performance. Examination of the data obtained in the particle size range 1.0 to 1.6 μm diameter with and without pulsing has led to the following observations:

- On the A side, there was no evidence of increased particle charge due to pulsing.
- On the B side, there is an indication of a 25% to 30% increase in particle charge due to pulsing on November 20. On November 21, the charge enhancement due to pulsing showed up only toward the upper end of the size range and only to the extent of about 15%. This indicates that the charge gain due to pulsing was varying with time during the test program.

The significance of these observations is that, although similar overall mass reductions were achieved by both pulsing systems, the mechanisms through which the enhancements were accomplished were quite different. On side A, the performance enhancement is thought to have been accomplished primarily by reduction of large particle emissions which seem to be associated with reentrainment. On side B, the increase in particle charge associated with pulsing is qualitatively consistent with the collection efficiency improvements (shown in Figure 3) measured for particles in the diameter range 1.0 to 1.6 μm. That is, the ratios of individual particle size-dependent migration velocities ranged from 1.05 to 1.15 when pulser-on conditions were ratioed to pulser-off conditions. These ratios for both the A and B sides are shown in Figure 7. Note that the pulser-on/pulser-off ratios for side A show essentially no enhancement for particle diameter less than 2.0 μm.

Electrical operating conditions for the T-R sets not pulsed were governed by the existing automatic controllers. Each pulsing system manufacturer established the operating conditions of its system. The waveforms delivered by the pulsing system are not presented in this paper due to a confidentiality agreement with the manufacturers. Generalized waveform, pulse width, and pulse repetition rate will be given in the final report. Also included will be averaged and detailed electrical readings of voltage and current, and power consumption for each system.

DISCUSSION

Although the pulsing systems installed at Lansing Smith were unable to allow the ESP to operate in compliance, it is of interest to consider the implications of the performance enhancements which were achieved. A practical method of determining these implications is to estimate the plate area equivalent of the performance gains effected by the pulsing systems. Unfortunately, since the mechanisms of performance enhancement are not described by existing physical models, a precise method of calculating the plate area equivalent is not available.

An estimation of the plate area equivalent of the performance gains, however, may be obtained by using the fractional efficiency data from the impactors, and the Deutsch equation, for individual particle sizes

$$\omega_i = \frac{V}{A} \ln \left(\frac{100}{100-\eta_i} \right) \qquad (1)$$

ω_i = apparent migration velocity for the i^{th} particle diameter,

where $\frac{V}{A}$ = ratio of volume flow to plate area, and

η_i = efficiency for the i^{th} particle diameter.

The impactor data sets from both chambers were used to compute ω_i values, which were used, in turn, to calculate new values of collection efficiency for each particle size band in a histogram distribution at larger values of specific collection area. Overall mass collection efficiencies were obtained by summing over the particle size distribution. (That is, $\eta = \Sigma P_i \eta_i$ where P_i is the fraction of the inlet mass in the i^{th} particle size band in the inlet particle size distribution.) Results from these calculations are displayed by the dotted lines in Figures 8 and 9. The solid lines labeled with ω_k were obtained with another method which will be discussed later. This calculation assumes that the size dependent migration velocities will remain constant if each chamber is increased to a larger specific collection area in the existing respective configurations. Although this assumption is subject to some question, it is believed that this method is the more conservative for extrapolating the results to larger specific collection areas.

Also shown in Figures 8 and 9 are mass train data obtained under the indicated conditions. Since the data from the mass trains show significantly different results in overall mass collection efficiency from those with impactors, these data were extrapolated to larger specific collecting areas graphically by drawing curves parallel to the curves obtained from the previously described numerical integration procedure with the impactor data. Results from this exercise are interpreted as follows for the $\sim$0.7% Na_2O level:

- On the A side, the extrapolation indicates that pulsing allows a performance level to be achieved at an SCA of 66.93 $m^2/(m^3/sec)$ (340 ft^2/1000 acfm) which would require an SCA of 77.76 $m^2/(m^3/sec)$ (395 ft^2/1000 acfm) without pulsing. This is equivalent to a 16% increment in plate area. The equivalent plate area enhancement is approximately the same for both mass train and impactor data sets.

- On the B side, extrapolation of the impactor data indicates that pulsing allows a performance level to be achieved at an

SCA of 64.96 $m^2/(m^3/sec)$ (330 $ft^2/1000$ acfm) which would require an SCA of 73.62 $m^2/(m^3/sec)$ (375 $ft^2/1000$ acfm) without pulsing. This is equivalent to a 14% increment in plate area. Similar extrapolation of the mass train data indicates a 32% gain in plate area (from 320 to 420 $ft^2/1000$ acfm).

The authors believe that these differing results were each representative of the ESP performance at the time the measurements were made. The wide variation in enhancement (14 vs. 32% is thought to be associated with the sensitivity of indicated enhancement to the level of sodium oxide actually present in the ash undergoing collection. Recall that with 1% Na_2O in the ash (Table 1), no enhancements were discernible.

Another approach for estimating the improvement in ESP performance due to pulsing was recently suggested by Feldman.[4] This approach is based on a modified Deutsch equation in the form,

$$\eta = 100\ (1-\exp-[(\omega_k A/V)^m])$$

in which η = overall mass efficiency,

ω_k = modified overall precipitation rate parameter,

A = collection area

V = volumetric flow rate, and

m = exponent depending on the inlet particle size distribution.

An "enhancement factor" based on this approach is defined as the ratio of the ω_k values for pulsed and unpulsed performance. Table 7 provides enhancement factors calculated by this definition for both sides of the ESP for the averaged mass train and impactor data sets at the ∿0.7% Na_2O level condition, with values of m of 0.4, 0.5, and 0.6. Efficiency versus SCA lines in Figures 8 and 9 are shown derived from the ω_k approach with m = 0.6. It should be noted, however, that this calculation procedure does not account for the particle size-dependent nature of the response to pulsing which was observed during this test program. It can be seen from the graphs that this method results in larger apparent values of plate area gain than does the more conservative method used by the authors.

CONCLUSIONS

Although several undesirable circumstances were encountered during the test program, it was possible to evaluate the capability of the pulsing systems for improving the performance of the hot-side ESP at Lansing Smith. The following conclusions have been derived from the evaluation program:

- With no sodium addition to the coal supply, the pulsing systems decreased penetration from 3.33% to 1.57% on the B side, and from 3.67% to 1.68% on the A side. These penetration reductions were the largest observed on an absolute value basis. However, neither system allowed the hot-side ESP to operate in compliance (0.1 lb/10^6/Btu, or 43 ng/J) or to approach level of performance (0.36% penetration)[5] achieved with sodium conditioning.

- With ∿0.7% Na_2O in the fly ash, the penetration (emissions) on the A side with pulsing decreased from 1.67 to 0.93% (mass train data), and from 2.01 to 1.25% (impactor data) penetration without pulsing. It must be noted that the pulser system on A side operated only during the testing period and not on a 24 hour basis.

- With ∿0.7% Na_2O in the fly ash, the penetration on the B side with pulsing decreased from 1.76% to 0.58% (mass train data), and from 1.82 to 1.17% (impactor data).

- For particle diameters smaller than about 1.5 μm, the changes in collection efficiency due to pulsing were relatively small and were near the resolution limits of the instrumentation. For particle diameters larger than 2.0 μm, significant improvements in collection efficiency as a result of pulsing were observed.

- The long-term capability of pulse energization to sustain a given level of performance improvement could not be determined due to the limited duration of the test program.

- These results were obtained with a hot-side ESP which had experienced performance degradation due to a sodium depletion process adjacent to the collection electrode. The results, therefore, are not necessarily applicable to cold-side applications where different charge transport mechanisms through the dust layer may be involved.

A more detailed presentation of results, along with discussions of possible mechanisms involved in the observed performance enhancements, will be presented in the project final report.

ENDNOTES

1. Wilson, R. R., et al. Guidelines for Particulate Sampling in Gaseous Effluents from Industrial Processes. EPA-600/7-79-028 (NTIS PB 290899) January 1979.

2. Rugg, D., et al. "Electrostatic Precipitator Performance with Pulse Excitation." To be Published.

3. McDonald, J. R., M. H. Anderson, R. B. Mosley, and L. E. Sparks. J. Appl. Phys. 51, pp. 3632, 1980.

4. Feldman, Paul L. "Pulse Energization: Present Status." Presented at the "Second Conference on Air Quality Management in the Electric Power Industry." January 22-25, 1980, Austin, Texas.

5. Gooch, J. P., et al. "Improvement of Hotside Precipitator Performance with Sodium Conditioning - An Interim Report." To be Published.

Table 1

LANSING SMITH PULSER EVALUATION
METHOD 17 MASS RESULTS

Date	Particulate Mass Loading, mg/DNm^3		Precipitator		Sampling	
	Inlet	Outlet[a]	Efficiency %	SCA $m^2/(m^3/sec)$	Location	Condition
NO SODIUM ADDITION						
11/11/80	15,786	526.4	96.67	65.26	B Side	Pulser Off
11/12/80	16,227	255.2	98.43	63.19	B Side	Pulser On
11/12/80	13,881	509.2	96.33	69.29	A Side	Pulser Off
11/13/80[b]	14,327	240.3	98.32	67.22	A Side	Pulser On
SODIUM ADDITION; - $\sim$0.7% Na_2O IN FLY ASH						
11/20/80	13,778	-----	-----	61.61	B Side	Pulser Off
11/20/80	16,479	66.4	99.60	61.42	B Side	Pulser On
11/20/80	14,602	128.2	99.12	64.37	A Side	Pulser Off
11/20/80	14,213	82.4	99.42	67.91	A Side	Pulser On
11/23/80	16,341	124.7	99.24	62.11	B Side	Pulser On
11/23/80	15,472	272.4	98.24	60.63	B Side	Pulser Off
11/24/80	14,991	337.6	97.75	63.09	A Side	Pulser Off
11/24/80	14,178	156.8	98.89	66.93	A Side	Pulser On
11/25/80	14,098	154.5	98.90	67.81	A Side	Pulser On
11/25/80	13,984	263.2	98.12	68.90	A Side	Pulser Off

---

a. All outlet loadings were determined at the outlet of the hot-side precipitator which is followed by a cold-side precipitator.

b. Probable coal change.

Table 3

TYPICAL COAL ANALYSIS

Date	11-11-80	
	As Received	Dry
% Moisture	4.82	-
% Carbon	69.82	72.66
% Hydrogen	3.89	4.09
% Nitrogen	1.71	1.80
% Chlorine	0.02	0.02
% Sulfur	0.85	0.89
% Ash	12.86	13.51
% Oxygen	6.69	7.03
% Volatile	25.98	27.30
% Fixed Carbon	56.34	59.19
Cal/g	6630	6966
Btu/lb	11935	12539

Table 2

RESULTS FROM SODIUM CONDITIONING TEST SERIES

Date	Precipitator		Sampling	
	Efficiency %	SCA $m^2/(m^3/sec)$	Location	Condition
3/14-19/80	99.88	63.78	A & B Sides	Baseline 1 - After Washdown
4/22-5/2/80	98.21	61.61	A & B Sides	Baseline 2 - After Degradation
5/14-24/80	99.64	63.39	A & B Sides	Conditioning 1 - Sodium Sulfate Conditioning to $\sim$1.0% Na_2O

Table 4

TYPICAL ASH ANALYSES
(EXPRESSED AS % OF IGNITED SAMPLE)

Date	11-11-80	11-23-80
Sample	No Sodium Addition	$\sim$0.7% Na_2O Level
Li_2O	0.08	0.09
Na_2O	0.39	0.88
K_2O	0.52	0.52
MgO	2.5	2.6
CaO	9.6	10.3
Fe_2O_3	5.8	5.6
Al_2O_3	33.2	33.1
SiO_2	38.8	39.0
TiO_2	1.7	1.8
P_2O_5	2.7	2.6
SO_3	1.1	0.88
LOI	17.0	17.5

Table 5

AVERAGE MASS LOADING CALCULATED FROM CASCADE IMPACTOR DATA

Date	Particulate Mass Loading, mg/DNm^3 Inlet	Particulate Mass Loading, mg/DNm^3 Outlet[a]	Precipitator Efficiency %	Precipitator SCA m^2/(m^3/sec)	Sampling Location	Sampling Condition
SODIUM ADDITION ~1.0% Na$_2$O IN FLY ASH						
11/17/80	15,699	110.7	99.29	59.79	B Side	Pulser On
11/17/80	15,699	125.2	99.20	59.79	B Side	Pulser Off
SODIUM ADDITION ~0.7% Na$_2$O IN FLY ASH						
11/21-22/80	15,657	183.6	98.83	64.83	B Side	Pulser On
11/21-22/80	14,784	269.0	98.18	64.83	B Side	Pulser Off
11/24-25/80	13,959	174.3	98.75	66.68	A Side	Pulser On
11/24-25/80	16,263	326.1	97.99	66.68	A Side	Pulser Off

---

a. All outlet loadings were determined at the outlet of the hot-side precipitator which is followed by a cold-side precipitator.

Table 6

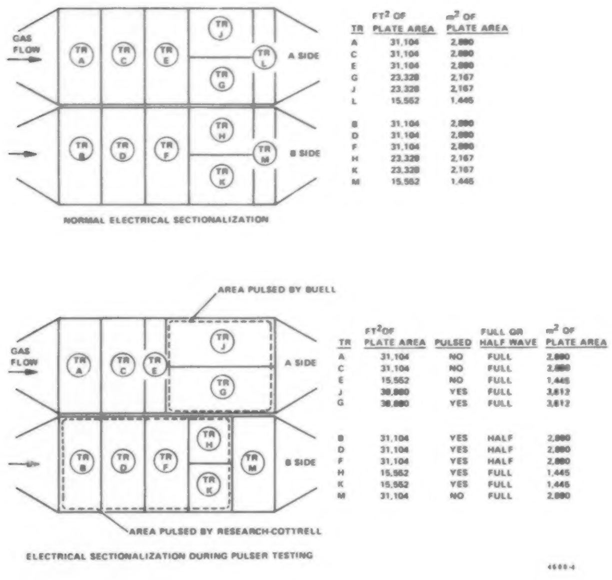
ULTRAFINE SYSTEM DATA

B Side

Size, µm	0.075	0.24	0.59	1.2
Percent Reduction	18	17	29	41

A Side

Size, µm	0.075	0.24	0.59	1.2
Percent Reduction	7	19	8	22


GAS FLOW
TR A
TR C
TR E
TR J
TR G
TR L
A SIDE
TR B
TR D
TR F
TR H
TR K
TR M
B SIDE
NORMAL ELECTRICAL SECTIONALIZATION
AREA PULSED BY BUELL
AREA PULSED BY RESEARCH-COTTRELL
ELECTRICAL SECTIONALIZATION DURING PULSER TESTING
4600-4

TR	FT^2 OF PLATE AREA	m^2 OF PLATE AREA
A	31,104	2,890
C	31,104	2,890
E	31,104	2,890
G	23,328	2,167
J	23,328	2,167
L	15,552	1,445
B	31,104	2,890
D	31,104	2,890
F	31,104	2,890
H	23,328	2,167
K	23,328	2,167
M	15,552	1,445

TR	FT^2 OF PLATE AREA	PULSED	FULL OR HALF WAVE	m^2 OF PLATE AREA
A	31,104	NO	FULL	2,890
C	31,104	NO	FULL	2,890
E	15,552	NO	FULL	1,445
J	38,880	YES	FULL	3,612
G	38,880	YES	FULL	3,612
B	31,104	YES	HALF	2,890
D	31,104	YES	HALF	2,890
F	31,104	YES	HALF	2,890
H	15,552	YES	FULL	1,445
K	15,552	YES	FULL	1,445
M	31,104	NO	FULL	2,890

Figure 1. Schematic of Lansing Smith Unit 2 hot-side ESP, transformer-rectifier arrangement.

Table 7

ω_k CALCULATIONS USING VARIOUS VALUES FOR m

m	Pulsing ω_k, cm/sec	No Pulse ω_k, cm/sec	Ratio
A SIDE			
Mass Trains[a]			
0.4	71.2	50.9	1.40
0.5	32.9	25.2	1.31
0.6	19.7	15.7	1.25
Impactors[b]			
0.4	62.0	46.5	1.33
0.5	25.6	23.5	1.26
0.6	18.1	14.9	1.21
B SIDE			
Mass Trains[c]			
0.4	98.0	53.4	1.84
0.5	43.2	26.6	1.62
0.6	25.0	16.7	1.50
Impactors[d]			
0.4	62.6	48.2	1.30
0.5	29.7	24.1	1.23
0.6	18.0	15.2	1.18

---

a. SCA = 66.5 m^2/(m^3/sec), η = 99.07 and 98.33
b. SCA = 64.83 m^2/(m^3/sec), η = 98.75 and 97.99
c. SCA = 61.44 m^2/(m^3/sec), η = 99.42 and 98.24
d. SCA = 66.68 m^2/(m^3/sec), η = 98.83 and 98.18

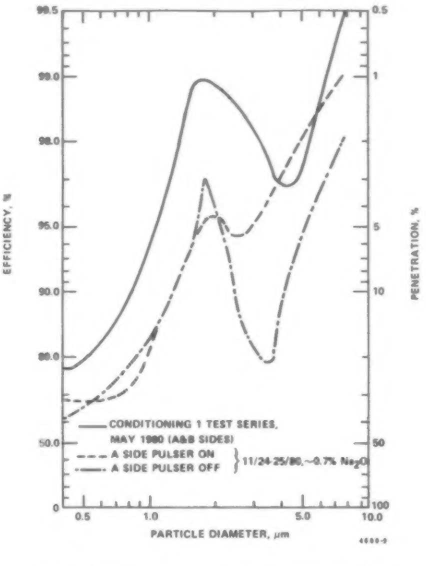


Figure 2. Fractional efficiency of A side ESP - pulser on and off.

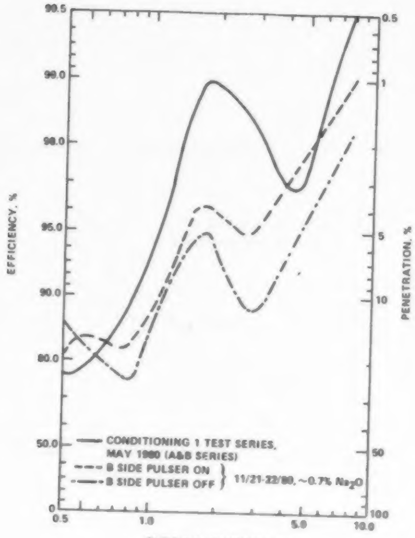


Figure 3. Fractional efficiency of B side ESP - pulser on and off.

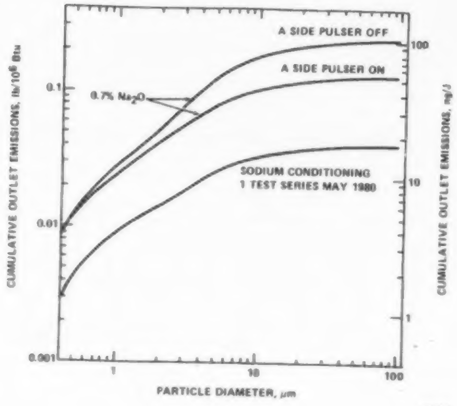


Figure 4. Cumulative outlet emissions versus particle diameter - A side impactor data, 11/24-25/80.[a]

a. Emission from hot-side ESP upstream of cold-side ESP.

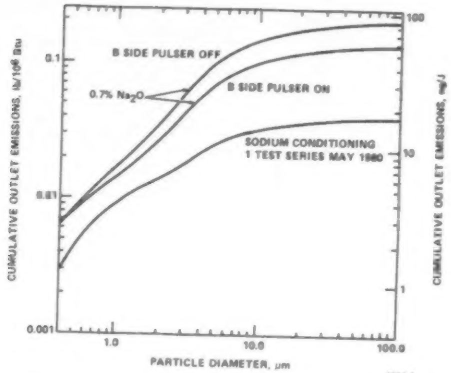


Figure 5. Cumulative outlet emissions versus particle diameter - B side impactor data, 11/21-22/80.[a]

a. Emission from hot-side ESP upstream of cold-side ESP.

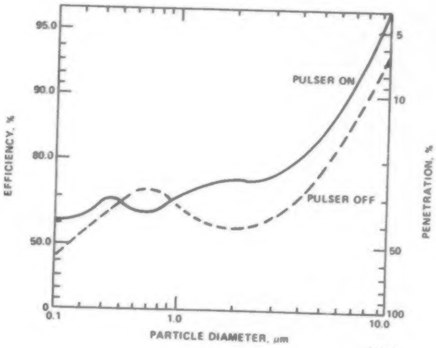


Figure 6. Fractional efficiency data from U.S. EPA, IERL, RTP, pulse energization tests.

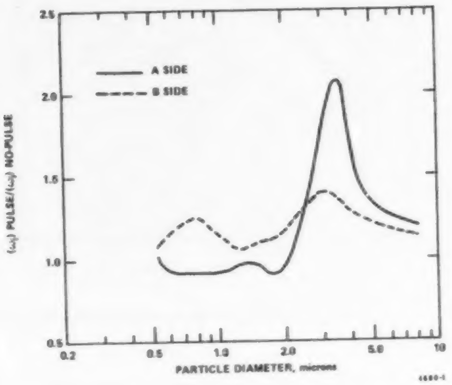
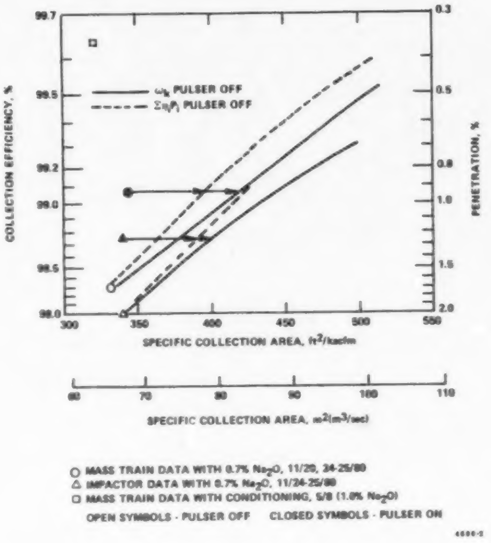
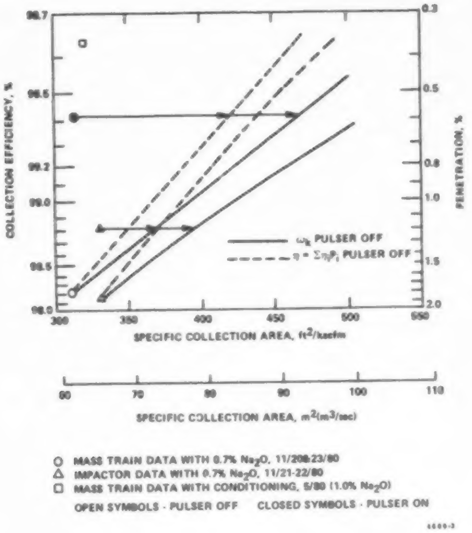


Figure 7. Effect of pulsing on the migration velocities of various particle sizes.



○ MASS TRAIN DATA WITH 0.7% Na_2O, 11/20, 24-25/80
△ IMPACTOR DATA WITH 0.7% Na_2O, 11/24-25/80
□ MASS TRAIN DATA WITH CONDITIONING, 5/8 (1.0% Na_2O)
OPEN SYMBOLS - PULSER OFF CLOSED SYMBOLS - PULSER ON

Figure 8. Effect of increasing collection area on collection efficiency of A side.



○ MASS TRAIN DATA WITH 0.7% Na_2O, 11/20&23/80
△ IMPACTOR DATA WITH 0.7% Na_2O, 11/21-22/80
□ MASS TRAIN DATA WITH CONDITIONING, 5/80 (1.0% Na_2O)
OPEN SYMBOLS - PULSER OFF CLOSED SYMBOLS - PULSER ON

Figure 9. Effect of increasing collection area on collection efficiency of B side.

A NEW MICROCOMPUTER SYSTEM AND STRATEGY FOR THE CONTROL OF ELECTROSTATIC PRECIPITATORS

By: K.J. McLean
T.S. Ng
Z. Herceg
Z. Rana

University of Wollongong
Wollongong. N.S.W. 2500
Australia

ABSTRACT

The paper outlines a new microcomputer control system for electrostatic precipitators. The system comprises three stages of development. In the first stage, a microcomputer, together with appropriate interfacing hardware, replace the existing analogue controllers and implement the present control strategy. In the second stage, the computer will carry out diagnostic analysis of voltage and current relationships for each zone and then initiate remedial action if necessary. In the third stage, the dust monitor output will be used to adaptively fine tune the control settings.

INTRODUCTION

Electrostatic precipitators are one of the most efficient and economical means of removing particulates from effluent gases at large coal-fired installations and are extensively used on boilers at electrical generating stations. The basic principle of operation, design and applications of electrostatic precipitators have been well documented (1, 2, 3).

The most efficient operating conditions occur when the voltages are maintained at or near their maximum value. Since Australian coals are low in sulphur content, the resistivity of the resultant fly ash is very high and this adversely affects the precipitator performance (4)(7)In particular, the 'back corona' formed on the collecting plates has the effect of reducing the sparkover voltage, increasing reentrainment and reverse charging of the suspended particles by the positive ions injected into the gas stream. The consequence of these effects is to reduce the precipitator's performance. Furthermore, at lower operating voltages, minor changes in their magnitude can significantly affect the efficiency of the precipitator.

In existing electrostatic precipitators, the corona voltages are regulated from some predetermined electrical conditions of each zone. These may vary with the manufacturer and the properties of the ash being collected but are usually based on spark rate, current density and minimum sparkover voltage or some combination of these. The final settings for the control systems is based on a series of special tuning tests which may be up-dated from time to time. This approach assumes that the optimum conditions remain unchanged for all operating modes, variations in the boiler and precipitator condtions and the inevitable coal variations.

With the recent development of reliabile optical monitors and the availability of relatively cheap microcomputers, we now have the opportunity to develop a new control philosophy for electrostatic precipitators.

The overall aim of the programme being undertaken by the Electrostatic Precipitator Research Group at the University of Wollongong is to develop a comprehensive computer control system comprising three development stages. In the first stage, a microcomputer, together with appropriate interfacing hardware, replace the existing analogue controllers and the microcomputer is programmed to adjust the corona voltage at five minute intervals to a level just below the sparkover voltage. Spark rate, current and voltage levels are monitored continuously and provision is made for a suitable protection and alarm system. In the second stage, the computer will carry out a diagnostic investigation of each zone using the voltage-current relationships and then initiate special remedial action if required. For the final stage, signals from the optical monitor, placed at the output of the precipitator and adaptive control techniques, will be used to fine tune the spark rate, voltage and current levels. The system described in this paper is designed to be installed to one pass of an electrostatic precipitator at Munmorah Power Station, N.S.W., Australia. Each of the development stages will now be discussed in more detail.

Stage 1 - Computer Control System

Figure 1 shows a block diagram of the power supply and existing control scheme for one zone of the electrostatic precipitator. The saturable reactor is controlled by a dc current supplied from the saturable reactor control unit. This control current is obtained from a full wave rectified voltage switched through an S.C.R. Its switching angle is controlled by feedback signals provided by the automatic controller and maintains a predetermined current and voltage level, and spark rate.

The area within the dotted line is the block diagram of the computer control system for five zones of one pass. The existing automatic analogue and the prototype computer control system can be separately switched into the same line providing the main control signal to the dc control for the saturable reactor.

A Rockwell AIM 65 single board microcomputer is used in this unit. It comprises a 6502 C.P.U. with eight K bytes of memory and six, eight bit bidirectional I/O ports.

The overall computer control system is shown in Figure 2. One analogue multiplexer is used to read voltages and currents for the five zones, using time multiplexing techniques. The spark status is counted independently for all the zones and is read continuously. The output control signals for the five zones are converted back to analogue voltages and transferred to the saturable reactor control units through voltage to current converters.

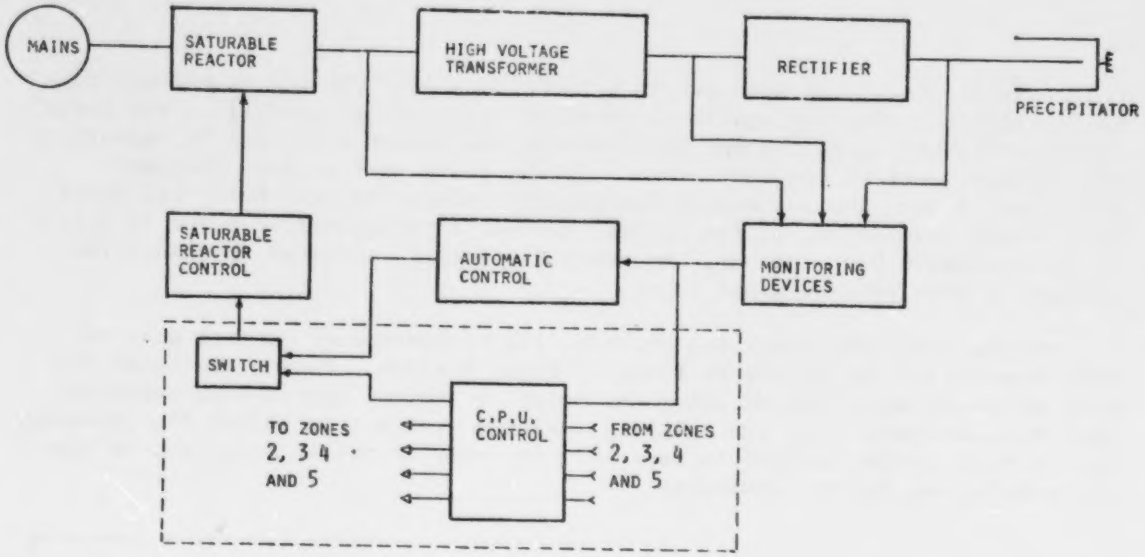

MAINS
SATURABLE REACTOR
HIGH VOLTAGE TRANSFORMER
RECTIFIER
PRECIPITATOR
SATURABLE REACTOR CONTROL
AUTOMATIC CONTROL
MONITORING DEVICES
SWITCH
C.P.U. CONTROL
TO ZONES 2, 3 4 AND 5
FROM ZONES 2, 3, 4 AND 5

Figure 1: Block diagram showing the interconnection of the existing analogue control system with the microcomputer.

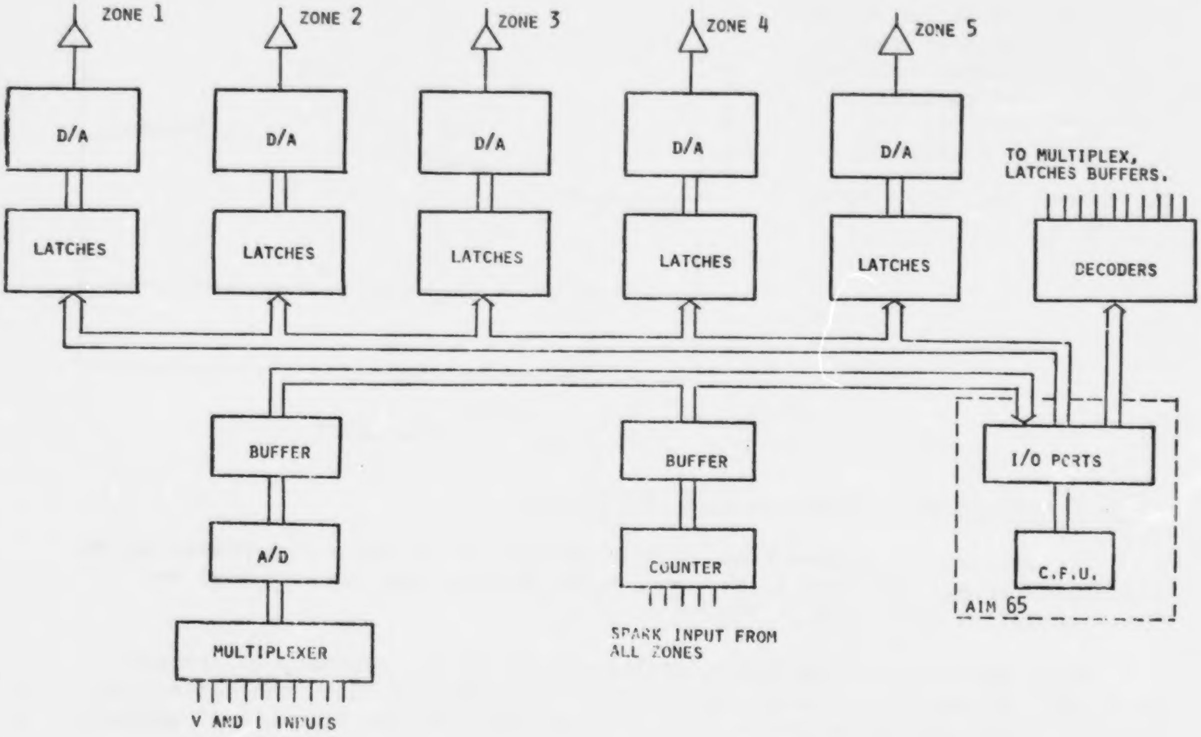

ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5
D/A
LATCHES
TO MULTIPLEX, LATCHES BUFFERS.
DECODERS
BUFFER
A/D
MULTIPLEXER
V AND I INPUTS
BUFFER
COUNTER
SPARK INPUT FROM ALL ZONES
I/O PORTS
C.P.U.
AIM 65

Figure 2: Overall organisation of the computer control system.

At this stage, the software is written to adjust the corona voltage to a value slightly below the sparkover level at five minute intervals. The normal control loop then goes through each zone at one second intervals to measure the voltage, current and spark rate. If the spark rate exceeds the predetermined value, the voltage is immediately reduced to just below the sparkover level. Similarly, if the current exceeds a predetermined value (possibly due to excessive back corona), the control signal is adjusted to reduce the current to some predetermined value.

At the time this paper was written, the microcomputer control unit had been constructed and tested at Munmorah Power Station. During the tests the dust emissions were reduced using the computer control system when compared with that obtained using the existing analogue system (see Figure 3). However, much more extensive testing is necessary in order to obtain more data to cover all possible operating conditions.

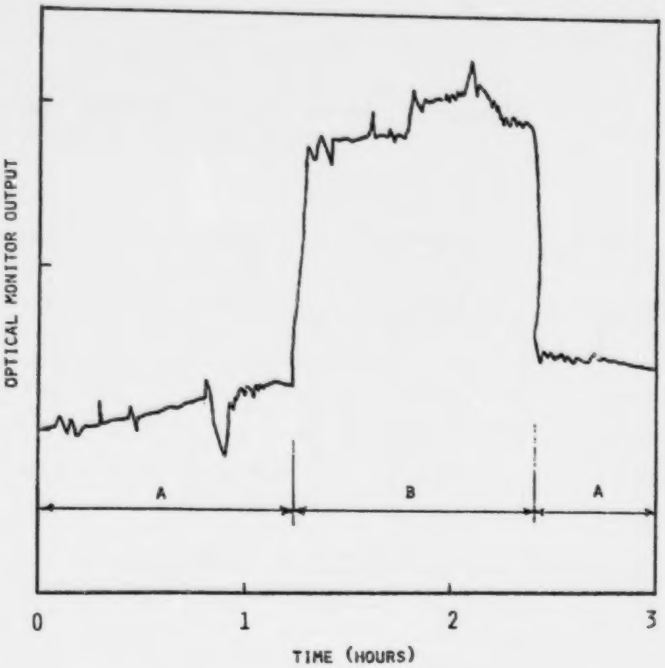


Figure 3: Variation of the optical monitor output with type of control

A. Computer control on.

B. Normal analogue control on

Stage 2 - Diagnostic Tests and Remedial Action

Preliminary tests have been carried out on two of the eight passes of an electrostatic precipitator at Munmorah Power Station and some typical V-I characteristics are shown in Figure 4.

These characteristics change with time and have a tendency to operate in a high voltage low current mode as dust layer builds up on the collecting plates. These characteristics can be changed as shown in Figure 4 if special rapping cycles are introduced.

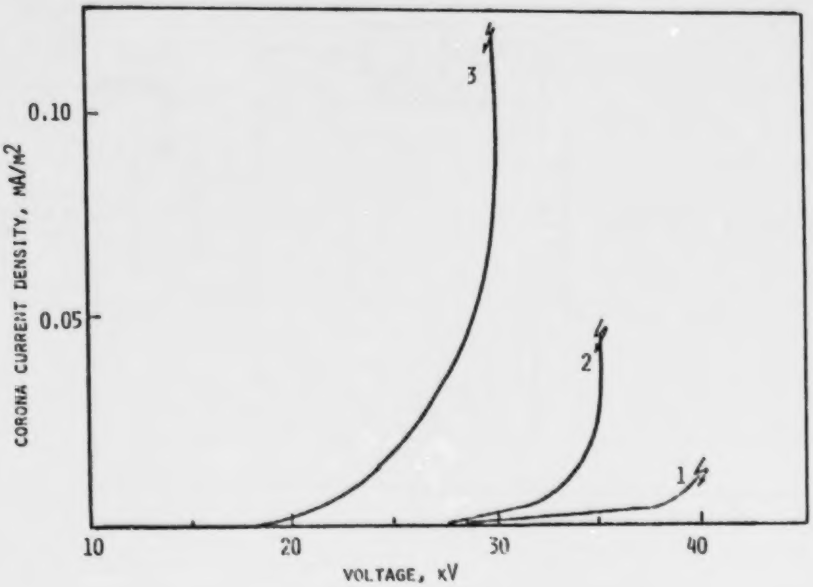


Figure 4: Variation of votlage current characteristics with collecting plate contamination.
1. Very dirty plates. 2. After period of intensive rapping.
3. Relatively clean plates.

In the second stage of the system development, the computer will be programmed to evaluate the characteristics of each zone and take the appropriate remedial action. For example, when a particular zone is operating in the strong back corona mode, indicated by curve 3, the computer could be programmed to detect this and adjust the control signal so that its operating point is close to or just on the onset of back corona.

A further extension of this mode of control would be to regulate the rapping of each zone. Once the effects of dust thickness have been characterised, an optimum rapping sequence could be programmed into the computer based on V-I characteristics. Special intensive rapping cycles can also be initiated for individual zones, aided by the switching off of the power supply, when the dust build up becomes excessive.

Stage 3 - Adaptive Control

In order to fully utilise the potential of a computer control system, certain optimal control theory could be made to apply to the precipitator. With the development of reliable dust monitors, the computer could be programmed to implement a model reference adaptive control system. Figure 5 shows the block diagram for such a system.

In Figure 5, G_1 to G_5 represent the invariant transfer function for the control system for each zone (see also Figure 1) and G_6 represents the time varying transfer function for the electrostatic precipitator. The adaptive

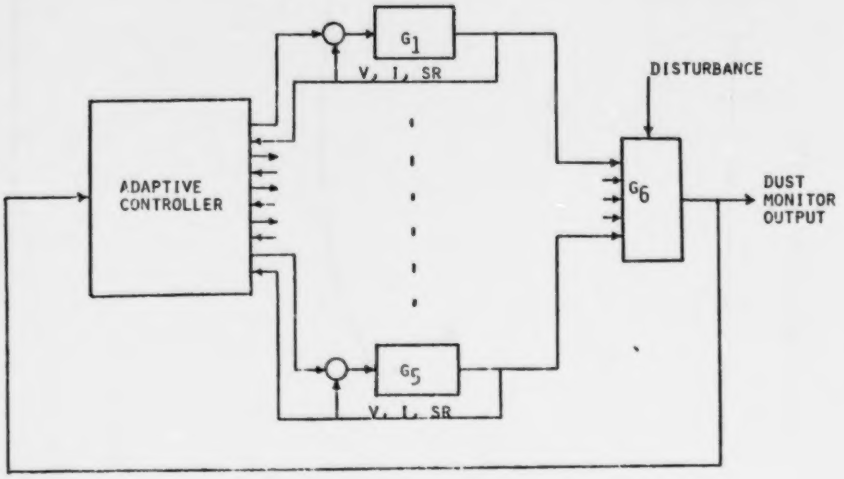


Figure 5: Block diagram of an adaptive controller.

controller continuously up-dates the parameters of G_6 based on the dust monitor output and the voltage, current and spark rate feedback from the control unit of each zone. Using certain optimal control techniques such as self-tuning regulations and minimum variance control techniques (5, 6), the settings for spark rate, current and voltage levels can be continuously adjusted to obtain the maximum possible performance of the electrostatic precipitator.

ACKNOWLEDGEMENT

The authors are grateful for the financial and technical support given by the Electricity Commission of New South Wales and the National Energy Research, Development and Demonstration Programme administered by the Australian Commonwealth Department of National Development and Energy.

ENDNOTES

1. White, H.J. Industrial Electrostatic Precipitation. Reading, Mass., Addison-Wesley, 1963.

2. Hall, H.J. Design and Application of High Voltage Power Supplies in Electrostatic Precipitation, J. Air Poll. Cont. Ass., 25: 132-38, 1975.

3. Oglesby, S. and Nichols, G.B. Electrostatic Precipitation. New York, M. Dekker, 1978.

4. McLean, K.J. and Kahane, R.B. Electrical Performance Diagram for Pilot-Scale Electrostatic Precipitators. (Presented to the Symposium on Transfer and Utilisation of Particulate Control Technology, Denver, U.S.A., 1978).

5. Astrom, K.J. Introduction to Stochastic Control Theory. New York, Academic Press, 1970.

6. Astrom, K.J., Borisson, V., Ljung, L. and Wittenmark, B. Theory and Application of Self-Tuning Regulators. Automatica, 13: 457, 1977.

7. Lamb, A.N. and Watson, K.S. Electrostatic Precipitation of Fly Ash from Low Sulphur Coal in Power Stations. (Presented to the Symposium on the Changing Technology of Electrostatic Precipitation, Adelaide, Australia, 1974).

ASSESSMENT OF THE COMMERCIAL POTENTIAL FOR THE HIGH INTENSITY IONIZER IN THE ELECTRIC UTILITY INDUSTRY

By: John S. Lagarias
Kaiser Engineers, Inc.
Oakland, California

Jack R. McDonald
Southern Research Institute
Birmingham, Alabama

Dan V. Giovanni
Electric Power Research Institute
Palo Alto, California

ABSTRACT

The High Intensity Ionizer (HII) has reached a level of development where projections can be made of its potential in the electric utility industry. Computer simulations have been conducted to predict the maximum electrostatic precipitator (ESP) performance enhancement of HII applications for high- and low-resistivity fly ash applications. Future electrostatic precipitator performance requirements have been forecast based on an assessment of possible changes to regulations for mass emissions, fine particulate, and opacity. A forecast is made of the equipment which may be used over the next 15 years for upgrading existing precipitator installations. Alternative means of upgrading ESP performance were also considered. We conclude that the HII may be one applicable method for upgrading electrostatic precipitators to meet possible more stringent regulations and may be used by as much as 20 to 25 percent of the upgrade market.

1. INTRODUCTION

This report examines the commercial potential for the High Intensity Ionizer (HII) to upgrade existing electric utility precipitators over the next 15 years. Situations where the HII may apply and the segment of the market which the HII may capture are estimated. In making the analysis, competing alternative processes for improving precipitator performance have also been considered, such as adding more specific collection surface area, gas conditioning, and pulse energization.

EPRI has been involved with the development of the HII technology since 1974 including benchscale, pilot, prototype, and full-scale testing. Much of the experimental evaluation of the HII has been conducted at the EPRI Arapahoe Test Facility in Denver, Colorado. The HII development has now reached a stage where projections of its commercial performance may be made. To assess the commercial potential of the HII, however, a brief review of the current ESP situation is appropriate.

Fly ash ESP's have been used by utilities since 1923, but it was not until the 1950's, when pulverized coal-fired boilers became common and started to increase significantly in size, that ESP performance became essential to utility operations. Since their initial usage, about 1,900 utility fly ash ESP's have been installed in the United States, most (1,400) since 1950. Of this number, 550 were installed in the last decade (1970-1980) including approximately 100 "hot" ESP's for high resistivity fly ash applications.

Over the past 30 years, the collection efficiency of installed ESP's has improved dramatically through advances in equipment performance and design. For example, the average design efficiency for fly ash ESP's selected in 1950 was 93.5%. By 1970, the average design efficiency had increased to 99.0% and, by 1980, performance specifications quite normally called for efficiencies in excess of 99.5%.

Today, however, ESP's face an uncertain future. Questions of applicability, cost, and most of all, reliable performance, are being raised. Changes in environmental regulations, particularly those involving opacity and fine particulate, stipulate levels of emission control which may be difficult to sustain. Competitive particulate reduction methods such as the use of fabric filter collectors or process modifications (solvent refined coal, combined gas/particulate controls, coal gasification, etc.) are starting to be used. These actions suggest that the potential of the electrostatic precipitator to the electric utility industry be reviewed critically. The issues are particularly significant as this country moves to a greater usage of coal.

The approach used in this analysis was to combine:

(1) An engineering assessment of the commercial performance and cost of the HII based on extrapolated results of the HII at the Arapahoe Test Facility;
(2) A scenario of possible future particulate regulatory changes;
(3) A survey of experienced designers, users, and scientists of ESP's as to the performance of existing utility fly ash ESP's;
(4) An identification of other available particulate control methods;
(5) An assessment of the type of upgrading that ESP's would require to meet the particulate scenario; and
(6) A projection of the commercial usage for the HII to the electric utility industry over the next 15 years.

In making an engineering assessment of the commercial performance and cost of the HII, we assumed that the increased charging capability of the HII demonstrated at Arapahoe could be obtained in full-scale units and incorporated into existing ESP's. This analysis would thus indicate the maximum performance we could expect from the HII.

To understand just what performance levels the utility ESP's would be required to meet in the future, it was necessary to create a scenario of possible future regulations which precipitator performance should address. We identified mass emissions, fine particulate, and opacity as being of greatest concern. For the purposes of our analysis, we assumed a number of regulatory changes to occur over the next 15 years which would require existing utility fly ash precipitators to be upgraded.

To assess the condition of existing precipitators, a survey was made of knowledgeable precipitator users, suppliers, and scientists. We asked for their assessment as to the ability of existing precipitators to comply with a scenario of assumed regulatory changes. The survey was entirely subjective and based on the best judgment and experience of those interviewed. The consensus was translated into a numerical assessment.

We identified the performance improvements that existing precipitators would have to meet and further identified competing technologies, in addition to the HII, that might be used to upgrade ESP's. Cost and performance comparisons were made of the available alternative upgrading methods and the HII which could be used to meet performance improvement previously identified. Comparisons were made by simulation studies of two specific installations for which performance data were available.

Combining all of the above information, we then forecast the number of existing ESP's which could require upgrading during each of the next three five-year periods, 1980-1984, 1985-1989, and 1990-1995. The number of installations where the HII might be used, and the potential magnitude of the HII market, were identified.

2. ASSESSMENT OF PERFORMANCE AND COST

Tests made by Southern Research Institute (SoRI) of the performance of an HII array on a pilot ESP at the EPRI Arapahoe Test Facility have demonstrated that the HII can charge individual fly ash particles to much higher levels than a conventional ESP. However, some loss of charge has occurred downstream of the HII, and methods are still to be developed to reduce this loss. For the purpose of this analysis, however, it is assumed that in a commercial installation the HII will be able to fully charge entering fly ash particles in agreement with theory and experimental results, and that an existing ESP will be able to collect the highly charged particles.

To evaluate commercial potential, an analysis was made of the capability of the HII, along with three alternative methods, to upgrade precipitators to meet certain target performance levels. Two existing precipitators were selected, one handling high resistivity fly ash and the other handling low resistivity fly ash. Precipitator and boiler data for the two installations are given in Table 3-1. The efficiency required for each precipitator to meet a target emission level of 0.1 lb/10^6 Btu was calculated and shown on Table 3-2. It should be noted that the two precipitators had significantly different ratings (180 and 92 SCA ft^2/1000 acfm).

Options for Upgrading ESP's

HII Addition

According to theory, the High Intensity Ionizer (HII), installed as a precharger to an existing precipitator, creates an extremely high initial charging field and is especially effective for fine particle charging. The HII would be used where, for a number of reasons, inadequate charging is obtained in a conventional electrostatic precipitator and would be powered independently of the precipitator power system.

The performance of the High Intensity Ionizer was evaluated at Southern Research Institute (SoRI) using an EPA/SoRI computer simulation model (EPA-600-7-78-111A) of an electrostatic precipitator preceded by an HII array. The expected HII-precipitator efficiency was calculated as a function of ionizer voltage (Figure 3-1). The ionizer voltage required to meet the desired outlet emission level was determined from this information. Computer analyses were also made of the anticipated performance of the High Intensity Ionizer added to an ESP for fine particulate under 2.5 microns (Figure 3-2). The results indicated that a substantial improvement could be obtained for the removal of fine particulate using the HII, especially when high resistivity fly ash is involved and thus could prove effective in meeting opacity requirements.

Additional Plate Area

Computer model studies were made to predict the anticipated efficiency of adding additional collecting surface to each precipitator. In each case, the computer model was corrected for nonuniform gas flow and for reentrainment loss. Precipitator efficiency was identified as a function of specific collection area (Figure 3-3). The specific collection area required to achieve a performance level of 0.1 $lb/10^6$ Btu was obtained using Figure 3-3.

Pulse Energization

At least two companies offer pulse energization systems to enhance particle charging using high voltage pulses superimposed on conventional DC voltage power supplies. Pulse energization would be proposed for high resistivity fly ash applications and is considered to be at an engineering demonstration stage. Model studies of the anticipated precipitator performance by the addition of pulse energization were calculated as projected increases in migration velocity based on published enhancement values.

Gas Conditioning

Conditioning of fly ash through flue gas additives is used where high resistivity fly ash conditions exist, especially where a utility may have switched from high sulfur to low sulfur coal. Sodium, sulfur, and proprietary chemical compounds have been used as conditioning agents. Over 150 flue gas conditioning systems are estimated to be operating or are in the process of being installed. Flue gas conditioning is in the commercial stage. Model studies of anticipated precipitator performance by gas conditioning were simulated through an increase in precipitator current and voltage as a result of the conditioning.

Precipitator Performance

The model simulations showed that permissible emissions could be achieved by the addition of the HII or by more plate area for both the low or the high resistivity fly ash precipitators. SO_3 gas conditioning and pulse energization would be effective for the high resistivity precipitator but could not improve the performance of the low resistivity fly ash precipitator to meet the permissible emission requirements (Table 3-3).

Capital Costs

Estimates of 1980 capital costs to upgrade the two precipitators were prepared following standard procedures. Cost data for cold side precipitators were used to estimate equipment costs for upgrading precipitators with different SCA (specific collection area) values.

Vendor-supplied equipment costs for the ionizer were used on a unit cost basis. Cost data for ionizer electrical components were updated to 1980 cost levels from an earlier EPRI study and adjusted for the number of TR sets used in the system.

Information on cost estimates for the equipment required in the SO_3 gas conditioning system was vendor-supplied.

Cost estimates for field material and installation labor were based on in-house experience with comparable equipment and on published cost factors.

Total capital investment required to achieve the desired performance for each upgrading alternative and 30-year levelized power costs are summarized in Table 3-4.

Total capital investment for each upgrading alternative was obtained by combining costs for equipment, field material, installation, engineering, and contingency.

For the high resistivity fly ash application examined, the capital cost of the High Intensity Ionizer would be substantially lower than the conventional plate retrofit. The operating cost for the HII would be higher principally due to the cost of steam addition to the purge gas (42 percent of the total levelized operating cost). However, SO_3 conditioning and possibly pulse energization would be more economical to achieve the desired performance level (0.1 lb/10^6 Btu).

The capital and operating cost for upgrading the low resistivity fly ash precipitator with the High Intensity Ionizer would be higher than a conventional plate retrofit. The other alternatives, SO_3 conditioning and pulse energization, could not give sufficient improvement to the performance of low resistivity fly ash precipitator to meet the desired performance level.

Operating Costs

The operating costs for upgrading by each of the alternatives were developed using EPRI economic premises and methodology (EPRI Technical Assessment Guide PS-1201-SR). The fixed operating cost included operating, maintenance, administrative labor, and material. Variable operating costs included precipitator and miscellaneous power, ionizer power, steam, chemicals, etc. Over the life of the plant, the operating costs tended to increase due to inflation. A single "levelized" value was computed using the "present worth" concept of money to represent the varying requirements for fixed and variable costs. A 30-year levelization factor for operating and maintenance costs and for the total capital requirement was computed on the basis of an EPRI-assumed inflation rate and discount rate. The yearly operating and capital costs were converted to 30-year levelized costs and represented in terms of power cost (mills/kwh). Operating cost data for each of the upgrading alternatives are also presented in Table 3-4.

3. A SCENARIO OF FUTURE PERFORMANCE REQUIREMENTS

Forecasting possible future regulatory changes is always difficult. It is particularly so at this time because of philosophical changes occurring in government administration and policy. However, it is conceivable that existing precipitators could require upgrading if particulate regulations became more stringent. For the purpose of this analysis, we have taken a scenario where changes in regulations would impact on upgrade requirements.

Mass Emission Regulations

The New Source Performance Standards (NSPS) for utility precipitators promulgated in 1980 lower permissible particulate emissions from 0.1 lb/10^6 Btu heat input to 0.03 lb/10^6 Btu. While existing precipitator installations are exempted from NSPS, stricter requirements for existing precipitators could occur as state and local regulatory agencies comply with the Clean Air Act and Amendments in updating State Implementation Plans (SIP's).

We have taken a scenario wherein changes in present regulations would require existing installations to meet the former NSPS standard (0.1 lb/10^6 Btu). In the immediate future, however, say up to 1985, we would anticipate that only a small number of the existing utility precipitators would have to meet a 0.1 lb/10^6 Btu requirement because most state and local regions are in reasonable compliance with total suspended particulate (TSP) standards. However, we could foresee that, by 1990, most existing ESP's could have to meet a 0.1 lb/10^6 Btu emission level as a result of changes to regulations.

Opacity Regulations

For the purposes of this study, we assume that changes to State Implementation Plans, local regulations, and federal requirements would tighten opacity regulations. Current requirements of the Clean Air Act Amendments call for State Implementation Plans to be updated by July 1, 1982. There already is a trend among regulatory agencies to require existing precipitators to meet 20% opacity as a minimum with others requiring a 10% opacity or even a clear stack. Many of the existing installations cannot meet a 10% opacity requirement, although it appears that precipitators installed since the late 70's are meeting 10% opacity in many instances.

Fine Particulate Regulations

Only one state, New Mexico, has a fine particulate emission regulation (particulate emissions, 2 microns or smaller, are not to exceed 0.04 lb/10^6 Btu). However, we can postulate a situation where specific fine particulate emission regulations are adopted by other states.

As a scenario, we would forecast that existing installations would not be subject to a federal fine particulate regulation but that some state or local agencies would adopt fine particulate emission regulations. For the purpose of our analysis, we consider that a small number of the existing precipitators would be subject to a New Mexico-type fine particulate emission regulation by 1985. By 1990, however, a larger number of the existing installations could be required to upgrade to meet fine particulate regulations.

4. ASSESSMENT OF EXISTING PRECIPITATOR PERFORMANCE

To estimate the immediate and future requirements for upgrading existing utility precipitators, a Delphi-type survey was conducted among 10 knowledgeable precipitator and utility representatives. A Delphi survey seeks to obtain a consensus on certain identified issues by reviewing the extreme positions taken in the survey and narrowing differences of opinion. This survey assessed the ability of existing precipitators to meet possible future regulatory requirements. Respondents were selected who, in the judgment of the authors, were knowledgeable of the operation of fly ash precipitators and the regulatory processes.

Questions asked were: Based on the interviewees' experience, what percentage of the existing utility fly ash precipitators

a) encounter high resistivity fly ash?
b) meet their existing particulate regulations?
c) could meet a 0.1 lb/10^6 Btu regulation?
d) could meet a 0.04 lb/10^6 Btu (minus 2 micron) regulation?
e) could meet a 10% opacity regulation?

The response (Table 4-1) was that, of the existing utility fly ash precipitator installations,

a) 30 percent experience high resistivity fly ash
b) 75 percent meet their existing regulations
c) 45 percent could meet a 0.1 lb/10^6 Btu regulation
d) 30 percent could meet a 0.04 lb/10^6 Btu (fine particulate) regulation
e) 20 percent could meet a 10% opacity regulation

Impact on Precipitator Performance Requirements

The Delphi-type survey estimated the present level of performance of existing fly ash precipitators. The assessment of regulations which may apply to these precipitators over the next 15 years established a scenario. A comparison can be drawn of the current level of precipitator performance to the potential regulation changes and a forecast made of precipitator upgrade requirements.

The following assessment is made of the number of existing utility fly ash precipitators that would have to be upgraded as a result of projected changes in regulations (Table 4-2).

1980-1984

Minor changes to mass, fine particulate, and opacity regulations are projected to occur. ESP's not always in compliance, or operating under variances, would be required to meet the existing particulate regulations on a regular basis. The Delphi survey estimated that 25 percent (350) of the existing precipitators would have been subject to upgrading. Of this number, 230 would be retired during this period for being over 30 years old. The remaining 120 ESP's would be subject to upgrade requirements.

1985-1990

Existing precipitators would be subject to stricter controls. The 1981 National Council on Air Quality report to Congress expresses strong concern over long-range transport and visibility and will precede congressional review of the Clean Air Act and Amendments. Changes to the Clean Air Act and Amendments cannot be forecast. However, as a scenario, we could project that 20 percent of the then existing utility fly ash precipitators would have to be upgraded to meet a 0.1 $lb/10^6$ Btu regulation (100 units). The current NSPS of 0.03 $lb/10^6$ Btu would continue to apply to new installations only.

An additional 15 percent of the existing precipitators might be subject to upgrading to meet new fine particulate regulations (30 units). If a 10% opacity regulation were adopted, an additional 20 percent of the existing precipitators would require upgrading (20 units). Thus, 45 percent of the existing precipitators were projected as subject to upgraded requirements in the 1985-1990 period (150 units).

Post-1990

A further tightening of particulate regulations may be projected to occur. In the post-1990 time period, 710 ESP's would still remain of the 1,400 units existing in 1980. One could project 300 ESP's requiring upgrading. Of this number, 230 units would be subject to a 0.1 $lb/10^6$ Btu regulation, 30 units subject to fine particulate regulations, and 40 units subject to opacity regulations. This number (300) would not include units upgraded in the 1985-1990 time period, or units which were upgraded to meet fine particulate regulations and thereby met opacity regulations. Two hundred thirty precipitators are assumed to be capable of meeting any of the hypothesized regulation modifications.

5. PRECIPITATOR UPGRADE ALTERNATIVES

Prechargers are only one of several alternatives being developed or already available which may be used to upgrade precipitators, and the High Intensity Ionizer is only one of several prechargers currently under development in the United States and Japan. Over the next 15-year period, only those alternatives which are currently either at a commercial or an engineering development stage would be considered as available for utility integration.

Selection of the appropriate alternative to improve precipitator performance is site specific. The precipitator should first be made to operate as effectively as originally designed. The internals must be in good shape or repaired; warped or misaligned plates should be straightened or replaced; rappers made to operate properly; flow adjusted; and power supplies made fully and effectively operable. An assessment can then be made of the performance limitations of the precipitator and a recommended course of action identified.

Mass Emission Reduction

Mass emission reduction requirements may vary substantially, from a condition where marginal precipitator performance is obtained (a regulation is met part of the time) to a condition where the current precipitator performance is completely inadequate. A mass reduction requirement is considered slight when penetration must be reduced by a factor of two. It is considered significant when penetration must be reduced by a factor greater than two.

Significant reductions in penetration will most often be achieved by adding new equipment such as pulse energization, the High Intensity Ionizer or a fabric filter, or by equipment modifications such as additional plate surface capacity.

Fine Particulate

The alternatives for upgrading existing precipitators to meet regulations involving fine particulate (<2 microns) will probably require the use of new technology such as pulse energization or the High Intensity Ionizer. Fine particulate removal will require a system which can apply sufficient forces to the individual small particles so as to separate them from the gas stream. Both pulse energization and the High Intensity Ionizer are intended to bring this about.

Opacity

All upgrading alternatives will reduce emissions to a degree, but significant reductions in opacity will depend on the ability of the alternative to reduce fine particulate emissions.

6. FORECAST OF MARKET REQUIREMENTS

The methods which could be used to upgrade existing precipitators to meet possible regulatory changes include: additional collecting plate area, the High Intensity Ionizer, pulse energization, or gas conditioning. No one method would be expected to be used for all situations. However, based on the projected performance of the HII through tests made at Arapahoe, and reports of the performance of other upgrade methods (1,2,3), one can examine future market requirements.

To forecast the market for the High Intensity Ionizer (HII) through 1995, the following assumptions were made:

- Those precipitator installations which must upgrade to meet current regulations will use either additional plate capacity or gas conditioning.

- The HII and pulse energization will prove to be effective, reliable, and commercially available by late 1983. Prototype and demonstration testing will have been completed by 1982.
- The HII will compete with plate addition and fabric filtration to meet fine particulate emission regulations.
- The HII will compete with the addition of more plate capacity to meet 10% opacity regulations.
- The HII will not compete with the addition of more plate capacity for most applications involving low resistivity fly ash.

Equipment performance is only one criterion used in equipment selection. Other criteria include cost, vendor marketing effectiveness, acceptance by industry, regulatory acceptance, and the performance and cost of competing alternatives. The number of utilities which would use the High Intensity Ionizer will depend, to a certain extent, on the number of major vendors offering it. Some utilities have a definite vendor preference based on previous experience and geographical location.

If several of the major vendors offer the HII, the number of precipitator installations which would consider the HII would increase proportionately. Conversely, if only one of the smaller vendors were to offer the HII, the number of HII installations would not be as great because that vendor reaches a lesser number of the utilities. Thus, to be used extensively, the HII--or any other alternative, for that matter--should be available through a significant number of the major precipitator vendors.

A forecast of the future of the approximately 1,400 precipitators in existence in 1980 is illustrated in Figure 6-1. We anticipate that older precipitators will gradually be retired, middle-aged precipitators will be upgraded to meet regulatory changes, and newer precipitators will not require any modification. The cumulative impact of these effects on the existing precipitators is shown starting for the five-year period to 1985, the 10-year period to 1990, and the 15-year period to 1995. An assessment of these changes is discussed below.

Assessment of the 1980-1995 Utility Precipitator Market

The assessment of the upgrade precipitator market for the 1980-1995 period is based on the following premises:

- Precipitators are projected to have a 30-year life and will be retired at a uniform rate (3.3%/year). There are approximately 1,400 utility fly ash precipitator units currently installed in the United States.
- The Energy Use Act would preclude the use of gas or oil for new utility installations after 1990, placing a greater emphasis on the use of coal as a utility fuel.
- Possible changes to mass, fine particulate, and opacity regulations may place increased performance requirements on existing precipitators.
- By 1990, at least one other new alternative, not presently identified, will have been developed and used to upgrade existing precipitators.

- New coal-fired installations will use either precipitators or fabric filter dust collectors, with electrostatic precipitators being used in slightly more than half of the new applications. New precipitator installations will also be able to incorporate the High Intensity Ionizer, other prechargers, or pulse energization in their design.

1980-1984

Existing precipitators upgraded during this period will use proven upgrading alternatives such as adding more plate capacity or gas conditioning. It is estimated that a two-year evaluation period and an additional one-year full-scale successful testing period would be required before the HII would have demonstrated acceptable performance to the utility industry. One or two demonstration-type HII units may be installed during this period but a substantial number of ionizer applications is not anticipated to occur. A shorter acceptance period is forecast for pulse energization although there may be some question about the charging of fine particulate by pulse energization.

1985-1989

During this period, 150 existing precipitators would require upgrading to meet possible new emission regulations. Approximately one-fourth of the precipitator installations (37) are estimated to encounter high resistivity fly ash. Upgraded precipitators will handle high resistivity fly ash by one of three methods: gas (SO_3) conditioning, pulse energization, or the use of a precharger such as the High Intensity Ionizer.

The SO_3 gas conditioning system has already been proven commercially while pulse energization and the HII have still to demonstrate reliable performance. However, concern over sulfate and SO_3 emissions may result in SO_3 conditioning systems not being universally acceptable for all high resistivity applications. Nevertheless, it is projected that 50 percent of all high resistivity fly ash precipitator upgrading applications would use SO_3 conditioning. The other 50 percent would be divided equally between pulse energization and the High Intensity Ionizer. Thus, an estimated 6.3 percent (nine) of the total high resistivity fly ash precipitators to be upgraded during this period would use the HII.

The precipitator applications encountering medium or low resistivity fly ash (113) have other upgrading alternatives available. SO_3 conditioning and pulse energization are not as effective for a low resistivity ash and would not be considered. Installations having medium or low resistivity fly ash could either add more plate capacity or use the HII.

The adding of pulse energization to existing power supplies for high resistivity fly ash applications could be quite attractive. It is still to be demonstrated, however, that sufficient useful power is developed by pulse energization to obtain the desired upgrading performance and that the operating long-term costs are acceptable.

It is forecast that the 113 existing low and medium resistivity fly ash installations would probably add additional plate capacity in 50 percent of the upgrade applications. Pulse energization would be used by 30 percent and the HII by 20 percent. The 20% share for the HII of the medium/low resistivity fly ash units being upgraded is equivalent to 15 percent of the total number of precipitators. Together with the 6.3 percent of the high resistivity fly ash applications that would use the HII, approximately 20 percent of the total number of precipitators being upgraded could use the HII. Quantitatively, this would be about 30 precipitator installations (Figure 6-1). Assuming the cost of an average HII installation for a 200-MW station to be $\$2.2 \times 10^6$, total investment for HII installations would be $\$66$ million $\times 10^6$ ($15.2 million per year).

1990-1995

During this time period, it is postulated that a large number (300) of the existing fly ash precipitator installations would be subject to opacity and fine particulate regulations. Precipitators erected prior to 1960 would have been retired.

Gas conditioning systems to upgrade precipitators could decrease if regulatory concern focuses on sulfate and SO_3 emissions.

With its ability to charge fine particulate, the HII could become an attractive method for precipitator upgrading as regulations for fine particulate control become prevalent.

The existing high resistivity fly ash installations to be upgraded (25 percent of total installations) would use alternatives such as pulse energization, gas conditioning, or the HII. If each alternative captured an equal share of the high resistivity upgrade applications, 11 percent of the total high resistivity upgrade applications would use the HII.

For the medium and low resistivity fly ash precipitators subject to upgrade (75 percent of the total), we postulate that the upgrading of the medium and low resistivity fly ash precipitators would be divided among four alternatives--the High Intensity Ionizer, additional plate capacity, pulse energization, or a fourth undefined, still to be developed system. Assuming 20 percent of these medium/low resistivity fly ash precipitators use the HII, 30 percent use pulse energization, and 50 percent use all other systems, then 15 percent of the total number would be upgraded with the HII. Adding the 11 percent of the high resistivity fly ash applications (and rounding off), we project that 25 percent (75 of the 300 upgraded precipitators) could use the HII (Figure 6-1). At an average cost of $2.2 million, a market of $165 million for the High Intensity Ionizer could result. Over a five-year period, this would represent an annual market of $33 million.

7. SUMMARY

Computer simulation studies have been made of the anticipated performance of the HII in full-scale installations assuming charge losses noted at Arapahoe could be overcome. Sizing data from two existing installations were used: one involving high resistivity fly ash and the second, low resistivity fly ash. Comparative capital and operating costs were also developed. Comparison analyses were made with alternative methods of upgrading precipitator performance including additional plate area, SO_3 gas conditioning, and pulse energization.

Each of the four methods was capable of upgrading the high resistivity precipitator to a target emission level of 0.1 $lb/10^6$ Btu. For the low resistivity precipitator, conventional plate addition and the HII were the viable alternatives.

Comparison of the capital and operating costs for upgrading a high resistivity precipitator showed SO_3 gas conditioning to have the lowest costs, followed by a conventional upgrade and the HII upgrade. Data were not available to project the cost for pulse energization. This example of one high resistivity precipitator is illustrative only and site-specific analyses at other installations would still be required. For the low resistivity precipitator, the lowest capital and operating cost could be obtained by a conventional upgrade over the HII for the example selected. Gas conditioning or pulse energization could not meet performance requirements.

A scenario of possible future regulatory requirements would indicate that tighter mass emission regulations, more stringent opacity regulations and fine particulate regulations might occur. On this basis the performance of existing precipitators to meet such regulations suggests that a substantial number of existing units would require upgrading. An assessment of the 1980-1995 utility precipitator market for the HII indicates the following:

a. One or two demonstration-type HII units could be installed during the 1980-1985 period, but a substantial number of ionizer applications is not anticipated to occur.

b. During the 1985-1989 period, it is estimated that about 6 percent of the total number of fly ash precipitators to be upgraded would use the HII for high resistivity application, and 15 percent of the total number of precipitators would use the HII for medium and low resistivity fly ash applications. About 30 precipitator installations could be upgraded with the HII during this period.

c. During the 1990-1995 time period, 11 percent of the total number of precipitators would use the HII to upgrade high resistivity precipitators and 15 percent of the total number would use the HII for low and medium resistivity fly ash applications. It is estimated that roughly 25 percent of the precipitators could be upgraded during this period with the HII.

The HII may be in an advantageous commercial position in the following situations:

a. High and low resistivity fly ash upgrade applications where fine particulate control and/or opacity are major concerns;

b. High resistivity upgrade applications with physical space or gas conditioning limitations;

c. High resistivity fly ash upgrade applications requiring significant emission reductions.

The HII may be in a disadvantageous commercial position in the following situations:

a. Either high or low resistivity fly ash applications needing slight emission reductions;

b. Upgrade applications where cost alone is the major concern;

c. Low resistivity fly ash installations where the existing collecting surface area is too small to benefit from HII upgrading.

REFERENCES

1. Feldman, P. L., and H. I. Milde, Pulsed Energization for Enhanced Electrostatic Precipitation in High Resistivity Applications, Symposium on the Transfer and Utilization of Particulate Control Technology, EPA-60017-79-044a, February 1979.

2. Lederman, et al, Sodium Conditioning Aids Precipitation, Symposium on the Transfer and Utilization of Particulate Control Technology, EPA/DRI, Denver, Colorado, July 1978.

3. Cook, R. E., Sulfur Trioxide Conditioning, Symposium on Electrostatic Precipitators for the Control of Fine Particles, EPA-650/2-75-016, January 1975.

Table 3-1

PRECIPITATOR AND BOILER DATA

	A (High Resistivity)	B (Low Resistivity)
Gas and Particulate Conditions		
Average gas flow, acfm	1,200,000	240,000
Gas temperature, °F	225	~ 300
Dust loading, gr/acf	2.91	0.5
Fly ash resistivity, ohm-cm	6.0×10^{12}	2.0×10^{9}
Particulate density, lbs/ft^3	141.7	162.3
Geometry and ESP Performance		
SCA, ft^2/1,000 cfm	180	92
Number of fields	3	2
Total plate area, ft^2	214,400	22,080
Plate to plate spacing, inches	9	9
Wire to wire spacing, inches	9	9
Operating average voltage, kv	35.3	46.7
Operating average current, nA/cm^2	3.5	42.5
Precipitator efficiency, %	96.7	91.75
Boiler Conditions (Estimated		
Boiler capacity, Mw	300	75
Turbine heat rate, Btu/kwh	9,016	7,871
Boiler efficiency, %	NA	87.3
Gross heat rate, Btu/kwh	NA	9,016

Table 3-2

PRECIPITATOR EFFICIENCY REQUIRED TO MEET UPGRADING REQUIREMENT

Installation	Fly Ash Resistivity (ohm cm)	Current Performance Efficiency (%)	Desired Performance Level (0.1 lb/10^6 Btu) (%)
A	High (6×10^{12})	96.7	98.9
B	Low (2×10^{9})	91.75	93.6

Table 3-3 COMPARISON OF UPGRADE PRECIPITATOR PERFORMANCE REQUIREMENTS

			Performance Level (0.1 lb/10^6 Btu)			
Precipitator		Existing Precipitator	Conventional Upgrade	Ionizer Upgrade	SO_3 Gas Conditioning	Pulse Energizer
A	High Resistivity					
	Average voltage KV	35.3	--	57(1)	45.6	--
	Current nA/cm^2	3.5	--	1.5(2)	50.4	--
	SCA ft^2/1,000 cfm	180	260	180	180	180
	Incremental plate area, $ft^2/10^3$ cfm	--	80	--	--	--
	Efficiency, %	96.7	98.9	98.9	98.9	98.9
B	Low Resistivity					
	Average voltage KV	46.7	--	70(1)	--	--
	Current nA/cm^2	42.5	--	2.5(2)	--	--
	SCA ft^2/1,000 cfm	92	120	92	--	--
	Incremental plate area, $ft^2/10^3$ cfm	--	28	--	--	--
	Efficiency, %	91.75	93.6	93.6	(3)	(3)

(1) Ionizer only.
(2) Ionizer current ma/ionizer.
(3) Performance level efficiency not reached.

Table 3-4 PRECIPITATOR UPGRADE COST COMPARISONS

			Performance Level (0.1 lb/10^6 Btu)			
Installation			Conventional Upgrade	Ionizer Upgrade	SO_3 Gas Conditioning	Pulse Energizer
A	High Resistivity ESP					
	Capital Cost	\$ x 10^6	3.32	2.6	1.96	1.29(1)
	Levelized Operating Cost(3)					
	Capital	mills/kwh	0.325	0.254	0.191	-
	Operating	mills/kwh	0.103	0.346	0.113	NA(1)
	Total Levelized Operating Cost	mills/kwh	0.428	0.600	0.304	-
B	Low Resistivity ESP					
	Capital Cost	\$ x 10^6	0.38	0.70	(2)	(2)
	Levelized Operating Cost(3)					
	Capital	mills/kwh	0.149	0.274	-	-
	Operating	mills/kwh	0.143	0.179	-	-
	Total Levelized Operating Cost	mills/kwh	0.292	0.453	-	-

(1) Estimated.
(2) Efficiency level is not achievable.
(3) 30-year levelized power cost.

Table 4-1 QUALITATIVE ASSESSMENT OF EXISTING UTILITY FLY ASH PRECIPITATORS
(Delphi Approach)

REVIEWER	HANDLE HIGH RESISTIVITY FLY ASH (%)	MEET EXISTING REGULATIONS (%)	COULD MEET A 0.1 lb/10^6 BTU REGULATION (%)	COULD MEET A 0.4 lb/10^6 BTU (MINUS 2 MICRON) REGULATION (%)	COULD MEET A 10% OPACITY REGULATION (%)
A	--	95	75	30	20
B	20	70	40	20	10
C	40	40-50	20	20	10
D	33	95	80	80	25
E	35	75	--	20	35
F	20	90	70-80	30-40	10
G	35	75	90	50	50
H	33	60	10	10	20
I	30	90	20	25	10
J	20	30	10	--	30
Range	20-40	30-95	10-90	10-80	10-50
Concensus* (%)	30	75	45	30	20

*Highest and lowest estimates discarded.

Table 4-2 FORECAST* OF UTILITY PRECIPITATORS REQUIRING UPGRADING

		Time Period			
		1980-1984	1985-1990	1990+	Total
A. Existing Precipitators		1,400	1,170	940	
B. Units Retired (3.3%/yr)		230	230	230	690
C. Precipitators Subject to Upgrade		1,170	940	710	
D. Do not Meet Existing Regulations	(% of A)	25	--	--	
	(No.)	350	--	--	
E. Would Require Upgrading	(% of D)	100	--	--	
	(No.)	120(1)	--	--	
F. Could Not Meet 0.1 lb/10^6 Btu Regulation	(% of C)	--	55	55	
	(No.)		520	390	
G. Would Require Upgrading	(% of F)	--	20	60	
	(No.)		100	230	
H. Meets F But Not 0.04 lb/10^6 Btu (minus 2 micron)	(% of C)	--	15	15	
	(No.)		140	110	
I. Would Require Upgrading	(% of H)	--	20	130	
	(No.)	--	30	30	
J. Meet I But Not 10% Opacity	(% of C)	--	10	10	
	(No.)	--	90	70	
K. Would Require Upgrading	(% of J)	--	20	60	
	(No.)	--	20	40	
L. Total Requiring Upgrade		120	150	300	570
M. Meet All Requirements					140
TOTAL					1,400

*Based on survey of knowledgeable precipitator specialists.
(1)Excludes precipitators scheduled for retirement.

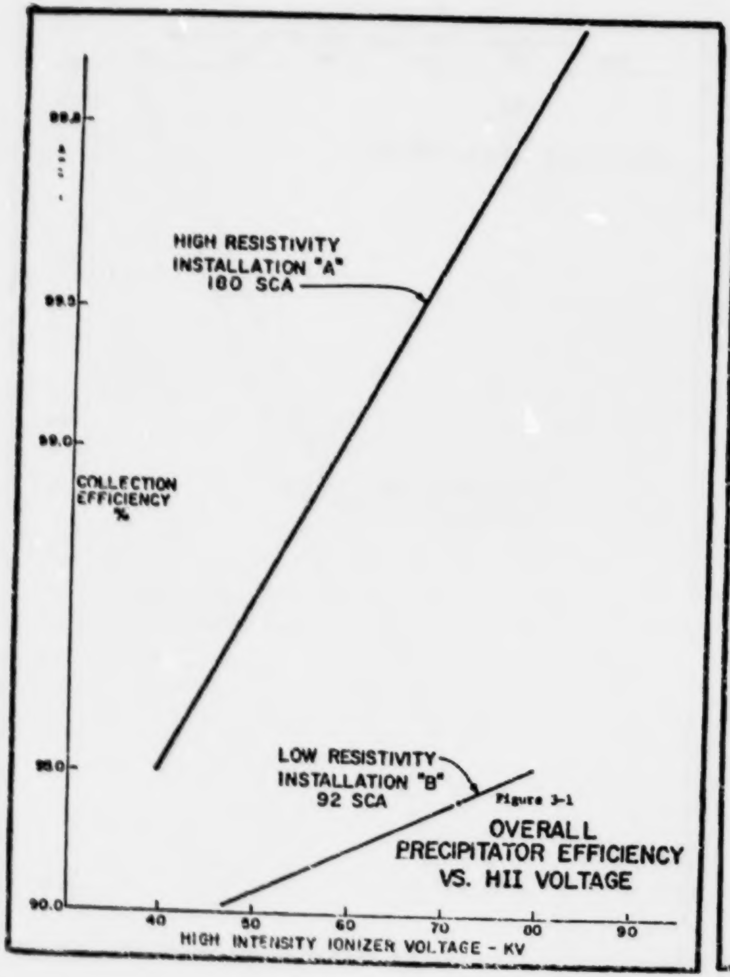
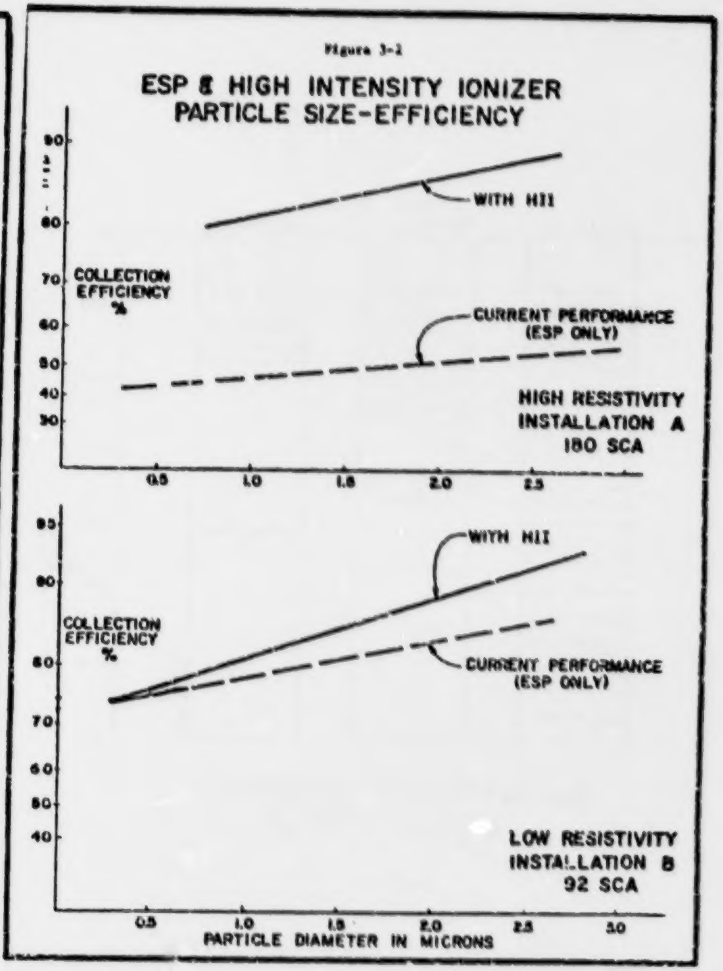


Figure 3-1

OVERALL PRECIPITATOR EFFICIENCY VS. HII VOLTAGE

Figure 3-2

ESP & HIGH INTENSITY IONIZER PARTICLE SIZE-EFFICIENCY



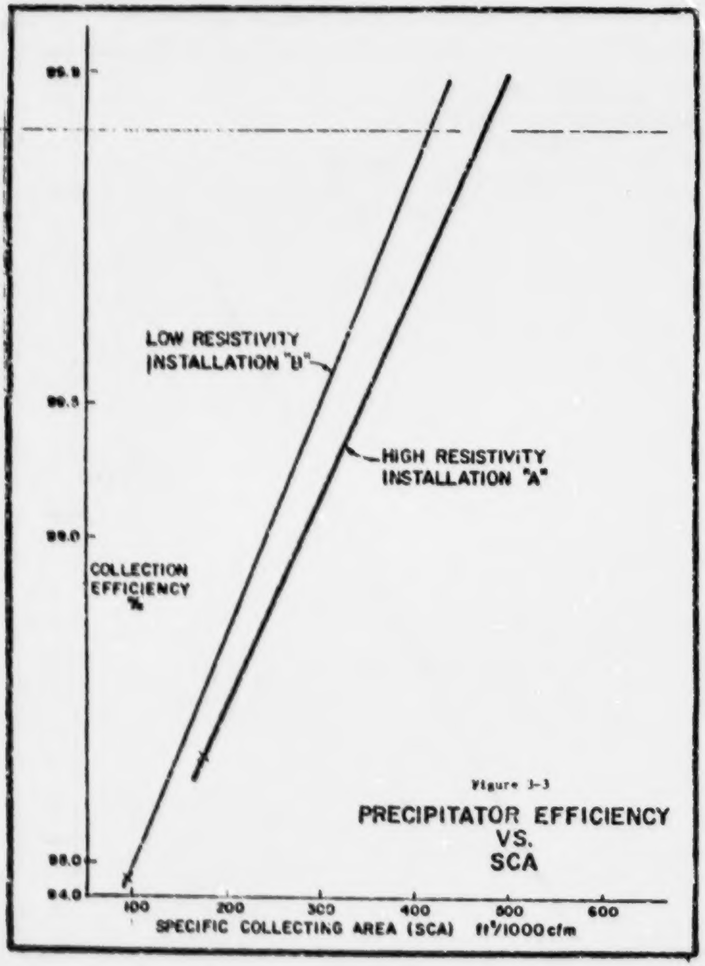


Figure 3-3

PRECIPITATOR EFFICIENCY
VS.
SCA

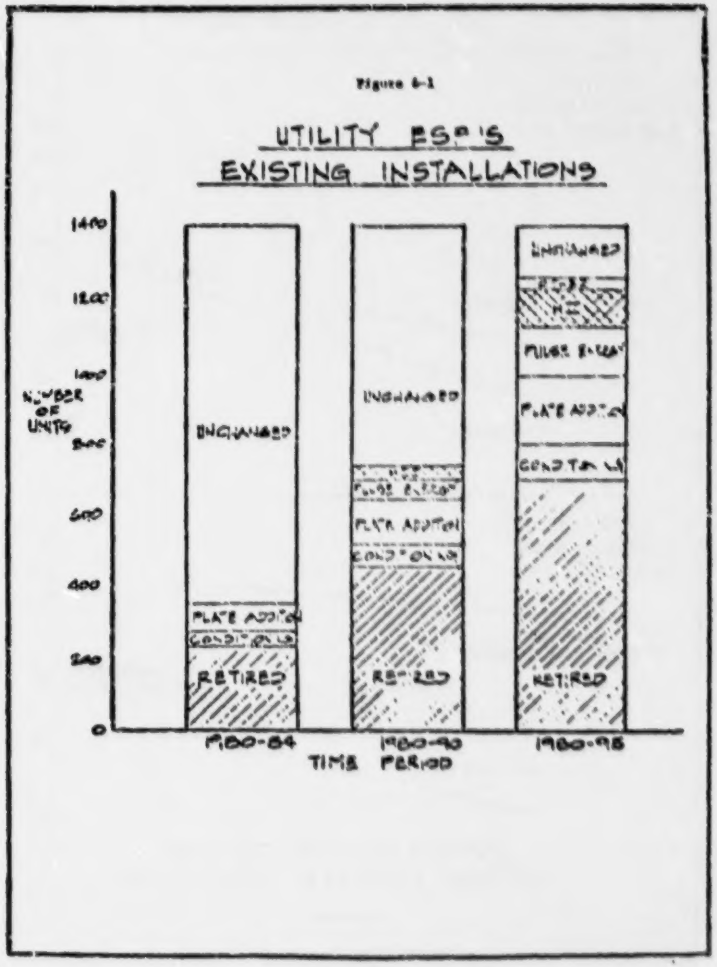


Figure 3-1

UTILITY ESP'S
EXISTING INSTALLATIONS

APPLICATION OF ENERGY CONSERVING PULSE ENERGIZATION FOR PRECIPITATORS
PRACTICAL AND ECONOMIC ASPECTS

By

Helge Hoegh Petersen
Preben Lausen

F.L. Smidth & Co. A/S
77, Vigerslev Alle, DK-2500 Valby
Copenhagen, Denmark

ABSTRACT

Performance of precipitators collecting high resistivity dust can be improved considerably by pulse energization. The energy consumption, however, is a major problem for its application on large precipitators, where considerable amount of energy is required to charge the precipitator capacitance to a high pulse voltage level. The energy conserving pulse energization system dealt with here solves this problem, as the energy stored in the precipitator during the pulse and not used in the precipitation process is recovered to be used for the next pulse application. Operating results and experience from full-scale field tests over a period of more than two years are presented. The tests have demonstrated that the system, utilizing high-power electronic components, has the required degree of reliability for practical application. Further, the obtained improvement of precipitator performance in relation to installation and operating costs makes it an attractive option to new precipitators for high resistivity dust as well as to existing precipitators with resistivity problems. Based on these findings, practical and economic aspects of installation and operation of the system on new as well as on existing precipitator installations are discussed.

INTRODUCTION

It has been known for many years that the performance of a precipitator collecting high resistivity dust can be improved by pulse energization.

By superimposing short duration high voltage pulses on the DC voltage by means of a suitable pulse generator, higher peak voltage is obtainable without sparkover. The use of pulse voltage gives a number of advantages including improved particle charging, higher collection field strength and better current distribution on the collection plates (1), (2).

Further, the discharge current can be regulated independently of the precipitator voltage by variation of pulse repetition frequency and pulse height (3). This makes it possible to reduce the discharge current to the threshold limit for back corona with a high resistivity dust, without reducing the precipitator voltage. This means more favourable electrical energization for such applications than is obtainable with conventional DC operation, where the current cannot be regulated independently of the precipitator voltage.

Earlier pulse energization work was hampered by the lack of reliable high-power switch elements for the pulse generator. Recent years technical progress has changed this situation. Various pulse energization systems are now under development in the U.S.A., Japan and Europe, with some of them at or very close to a commercial stage.

An inherent problem in pulse energization is the considerable amount of energy required for repetitive charging of the precipitator capacitance to a high pulse voltage level. Only a minor part of this energy is necessary for the discharge current in the precipitator. For reasons of economy, recovery of the surplus energy is important, particularly for pulse energization of large precipitators.

Some of the pulse energization systems under development are capable of conserving the capacitive pulse energy by recovering it from the precipitator after the pulse and using it for the next pulse. Such an energy conserving pulse energization system developed by F.L. Smidth (3) is described in the following, and the results obtained from industrial scale tests are presented.

F.L. SMIDTH ENERGY CONSERVING PULSE ENERGIZATION SYSTEM

General Principle

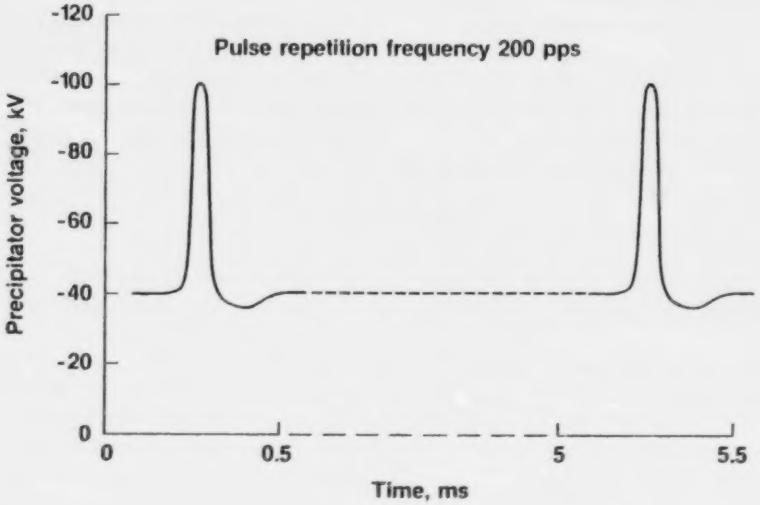


Figure 1. Precipitator voltage wave-form.

The system is used with conventional precipitators and does not require any special electrode arrangements. Short duration high voltage pulses are repeatedly superimposed on an operating DC voltage as shown in Figure 1. The pulse duration is within the range 50-200 µs, and pulse repetition frequencies from 25 to 400 pulses per second are used.

The level of the DC voltage depends on dust and gas characteristics. For high resistivity dust the DC voltage is maintained at or slightly below corona onset in order to extinguish the corona discharge after each pulse. This allows control of the discharge current by means of pulse height and repetition frequency.

Idealized wave-forms of the precipitator pulse current and voltage are shown in Figure 2. During the first half of the pulse time a negative current flows from the pulse generator to the precipitator, charging the precipitator capacitance from the operating DC voltage level to the pulse peak voltage.

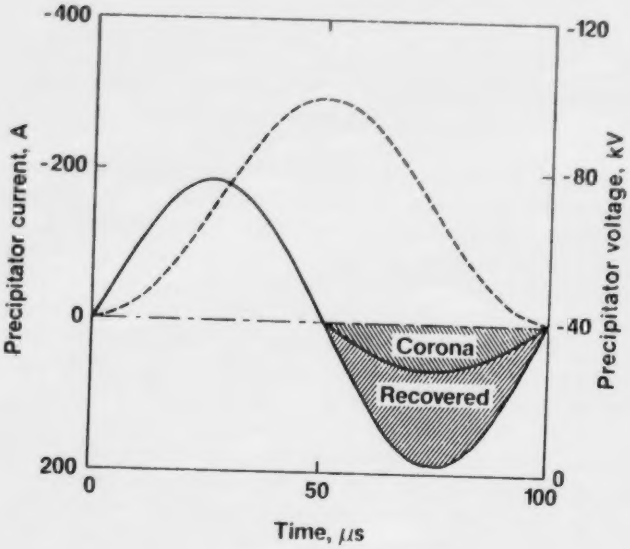


Figure 2. Ideal wave-forms of precipitator current and voltage.

For high pulse voltages only a minor part of this charge is emitted as discharge current during the pulse in order to maintain a suitable collection plate current density. The remaining and major part of the charge is returned to the pulse generator as a reversed current flow during the second half of the pulse time, thus bringing the precipitator voltage back to the operating DC voltage level, refer Figure 2.

The Energy Conserving Pulse Energization System

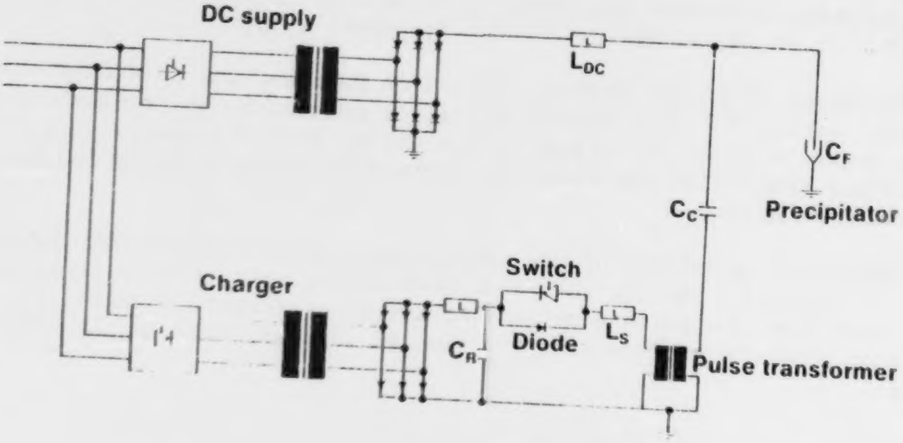


Figure 3. The F.L. Smidth energy conserving pulse energization system.

Figure 3 is a basic diagram of the energy conserving pulse energization system. The DC operating voltage is maintained by a DC supply with a blocking inductor L_{DC} preventing the pulse voltage from entering the supply. A coupling capacitor C_C blocks the DC operating voltage from the pulse transformer. The pulse circuit includes a charger supplying a storage capacitor C_R, a thyristor switch, a feed-back diode, and a series inductance L_S. The storage capacitor C_R, the series inductance L_S together with the pulse transformer leakage inductance, the coupling capacitor C_C, and the precipitator capacitance C_F form a series oscillatory circuit.

The storage capacitor C_R is charged to a controlled DC level by the charger. The thyristor switch is turned on, and the precipitator represented by the capacitance C_F is charged to the maximum pulse voltage level by the first half period of the oscillatory current. Because of the series oscillation, the energy supplied to C_F and not used for the corona discharge is returned to C_R through the feed-back diode by the current in the second half period. During this interval, the thyristor switch is turned off, and the current in the pulse circuit is blocked until the next ignition of the thyristor switch. The returned energy is stored in C_R during the interval between the pulses and is used for the next pulse.

An industrial precipitator may have a capacitance of 30-40 pF per m^2 (3-4 pF per square foot) collection area. Charging this capacitance to a high pulse voltage level a large number of times per second requires a considerable quantity of energy. Depending on pulse voltage level and repetition frequency, the charging energy might amount to several times the energy absorbed by the precipitator as useful corona discharge energy. For reasons of economy, recovery of the charging energy is consequently extremely advantageous for pulse energization of large precipitators (4).

GENERAL ARRANGEMENT

Industrial versions of the energy conserving pulse energization system are now being manufactured in the United States as well as in Europe by manufacturers, who also provide field service and stock spare parts. It is presently available in two standard unit sizes capable of energizing a precipitator field or cell with a collection area of 2500 m^2 (25000 square feet) up to 3000 m^2 (30000 square feet), depending on unit size, gas temperature and precipitator duct width. Larger units, capable of energizing up to 5000 m^2 (50000 square feet) of collection area each, are being developed and will become available early 1982.

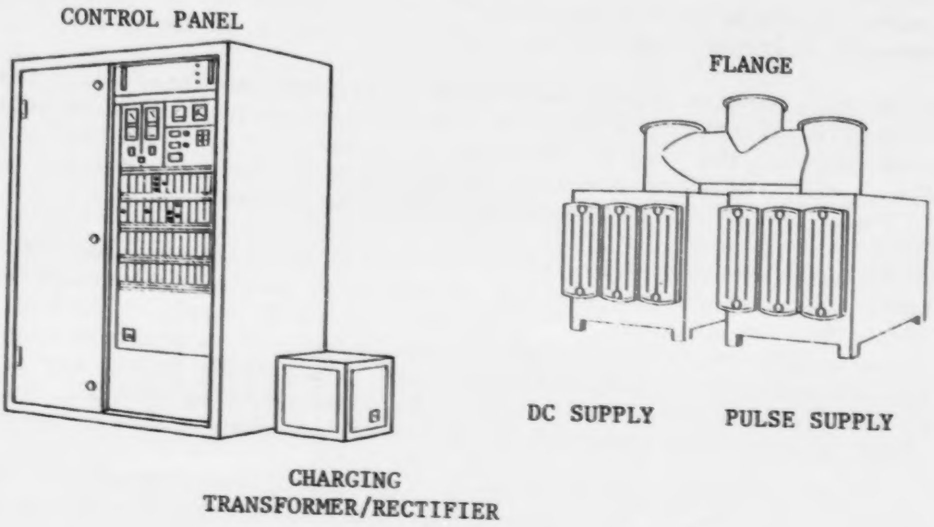


Figure 4. Arrangement of the pulse energization system.

A system for energizing one field or cell comprises the following equipment, refer Figure 4:

A. A control panel containing
  - Thyristor controllers for the DC high voltage supply and pulse charger
  - storage capacitor
  - thyristor switch for firing the pulses
  - feed-back diode for returning the charge from the precipitator to the storage capacitor
  - series inductance for matching circuit impedance to precipitator capacitance

- instruments for measuring DC voltage level, pulse peak voltage, precipitator current, and pulse repetition frequency
- manual controls
- automatic controls continuously adjusting DC voltage level, pulse peak voltage and pulse repetition frequency for optimum precipitator efficiency on basis of criteria related to control of corona discharges between pulses, total precipitator current, sparkover rate and sparkover intensity. The automatic controls further ensure fast precipitator voltage recovery after sparkover.

B. A transformer/rectifier for charging of the storage capacitor to a controlled voltage level corresponding to the desired pulse peak voltage.

C. A pulse power supply comprising the pulse transformer and the coupling capacitor in a common oil tank. The tank further contains a voltage divider for direct high voltage measurements. The precipitator can be connected either to the pulse supply or to ground for safety, through a manually operated high voltage change-over switch in the oil.

D. A DC high voltage supply comprising an oil emerged three phase transformer/rectifier with a blocking inductor preventing the pulse voltage from entering the supply. By means of a manually operated high voltage change-over switch in the oil, the precipitator can be connected either to the DC supply or to ground for safety during repairs.

Where pulse energization systems are installed at an existing precipitator installation the existing conventional single phase transformer/rectifiers may be used instead of the 3 phase DC supply. The single phase transformer/rectifier would have to be tied in with the controls for the pulse energization system. Also a smoothing filter for reduction of its ripple voltage would have to be added together with the necessary blocking inductor to prevent the pulse voltage from entering the DC supply.

Installation of the pulse system at existing or new precipitator installations is simple. The pulse power supply and the DC high voltage supply may be placed on the precipitator roof for direct connection to the field, or they may be placed at any other suitable outdoor or indoor location in the vicinity of the precipitator, and connected to this through high voltage busbars protected by trunking.

Where the size of the fields or cells is relatively small two fields or cells may be energized from the same pulse energization unit.

The control panel requires a dust-free environment and ambient temperatures maintained between 0°C (32°F) and 40°C (104°F).

For 6 mobile test and demonstration pulse energization units, 2 of which were manufactured in Europe and 4 in the United States, a suitable environment for the control panels was obtained by placing them in a 20' container with filtered ventilation, and heating and cooling facilities.

Similar control house arrangements may be advantageous also for permanent installations, particularly at existing precipitator installations where building layout makes it difficult to find suitable space and environment for the control panels. Further, the container solution has the advantage of minimizing field wiring work and installation time. Up to four control panels serving four high voltage units may be placed in one container.

Remote control and remote instrumentation is easily incorporated, either in a separate small remote control panel or built into a central control panel placed at any desired distance from the pulse energization system.

FULL SCALE TEST RESULTS

Precipitator for a Lime Burning Rotary Kiln

From early 1979 full scale tests have been carried out on a precipitator dedusting the 350°C hot exit gases from a 290t/24h lime burning rotary kiln in Denmark. The precipitator consists of two fields in series with collection areas of abt. 1100 m^2 and 1400 m^2, respectively. In the first field the duct width is 300 mm, and the discharge electrodes are of a rigid pin-type design. In the second the duct width is 250 mm, and the discharge electrodes are of the conventional 2.7 mm diameter helical type. The gas velocity is about 0.6 m/s, giving a total treatment time of 12 seconds.

The gas volume treated in the precipitator is about 115,000 m^3/h, temperature about 350°C, the water content about 15% by volume, and the dust load about 20 g/m^3. Particle size median is about 17 μm and dust resistivity varies from about 10^{10} to 10^{12} ohm·cm, depending on temperature, raw materials and kiln operation.

Each of the fields can be energized from either a pulse energization system or a conventional single phase, full-wave raw rectified DC power supply.

The precipitator efficiency and the w_k migration velocity were determined from measurements of the inlet and outlet dust concentrations and the gas volume flow rate. An improvement factor was defined as the ratio between the w_k values for pulse and DC energization for optimum operation conditions. The results confirmed earlier findings with a double pipe test precipitator (3), which showed that the improvement factor was strongly dependent on the degree of back ionization as judged from resistivity measurements and the corresponding current-voltage curve for DC energization, refer the table below.

OPERATION CONDITION	w_k IMPROVEMENT FACTOR
No back ionization, 10^{10} ohm·cm	1.1
No back ionization, 10^{11} ohm·cm	1.2
Moderate back " , 10^{12} ohm·cm	1.6
Severe back " , 10^{13} ohm·cm	2.2

During 1980 the pulse system has been running continuously on the first section of the precipitator with a total of about 6500 hours of operation without operation failure or need for service, and thus proved that the system has the required degree of reliability for practical application.

Precipitator for a 4-Stage Preheater Kiln

Two mobile pulse units have been operated for about 3 months on a precipitator for a 2800 t/24 h, 4-stage preheater cement kiln with raw mill in Spain. The installation has a conditioning tower in parallel with the raw mill in order to maintain a gas temperature of about 150°C, which is necessary to prevent back ionization (5). The precipitator has two chambers each with two fields in series with a collection area of about 2500 m^2 per field.

The gas volume treated is about 390000 m^3/h, and the dust load about 30 g/m^3. Particle size median is about 5μm.

The degree of back ionization can be controlled simply by reducing the water injection in the conditioning tower, which results in higher temperature, reduced moisture content, and higher dust resistivity.

One pulse unit supplies one field, and each of the four fields can be connected to a pulse unit. The dust emission can be measured at each of the chambers separately, and the installation thus makes it possible to test performance of pulsing on the two inlet fields, the two outlet fields, and the two fields in one chamber.

During the tests the temperature has been varied between 140 and 200°C, the moisture content in the range 15-8% by volume, and the dust resistivity from 10^{11} to $5 \cdot 10^{12}$ ohm·cm. This resistivity is measured on samples of dust scraped off the collection electrodes. Samples from the dust extraction equipment show resistivities about one decade lower.

Through these ranges of variation the w_k improvement factor remained constant at about 2 calculated for the pulse energized part.

ECONOMICS

Capital Expense for New Installations

Pulse energization can be used either to improve the performance of an existing precipitator, or to reduce the required collection area for a new precipitator installation for a high resistivity application.

The w_k improvement factor used above is useful, since the necessary collection area is inversely proportional to w_k. The earlier showed relationship between w_k improvement factor and resistivity level found for the lime kiln precipitator can be transformed into a set of curves as shown in

Figure 5, which illustrates the saving in collection area for pulse energization compared with DC energization.

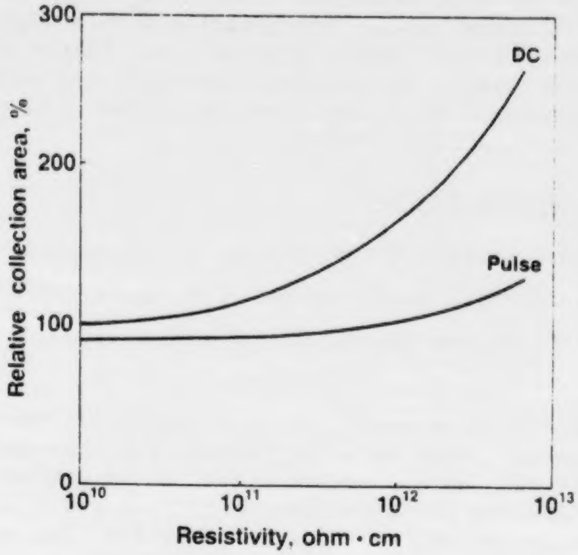


Figure 5. Relative collection area for DC and pulse energization.

The equipment cost on installed basis of the described type of pulse energization system is presently in the order of $6 per square foot of collection area energized. Further development of the technology, larger units and the general downward trend in prices of high power electronic switch elements can be expected to lower this figure in the future. However, already at a cost of $6 per square foot of plate area energized pulse energization becomes economically interesting for new installations even at medium level resistivities producing moderate w_k improvement factors.

This can be shown by the following simple way of reasoning with an improvement factor of 1.5 as example. The cost of pulse energizing two square feet plate area would be 2 x 6 = $12. With an improvement factor 1.5 the two square feet of pulse energized plate area would perform as well as 2 x 1.5 = 3 square feet of plate area energized with conventional DC. There is thus saved one square foot of plate area by using $12 for the pulse energization system. With costs of new large precipitator installations going as high as $22 per square foot of collection area on installed basis for a 500 MW unit it is seen that pulse energization has a considerable potential for savings with high resistivity fly ash.

Upgrading of Existing Installations

For upgrading of older precipitators pulse energization, where applicable, may be preferred to SO_3 conditioning for its simplicity, low power requirements, high reliability and low maintenance costs characteristic of solid-state TR sets.

For a backfit situation, assume a cold side precipitator on a 500 MW (net) plant with a SCA=300 square feet per 1000 ACFM achieving 97% efficiency on a high resistivity ash. In such cases an SO_3 conditioning system having an enhancement factor of 2 on migration velocity w_k might be a logical choice to achieve 99.4% efficiency. Pulse energization with a similar enhancement factor would also be a very viable alternative. Either of these would be much less expensive than adding an additional precipitator with SCA = 300 to achieve about 99.4% efficiency. Some cost comparisons for this case may be noted as follows; (1.9 million ACFM at 300°F).

Capital Expense

New Backfit ESP at $22/sq.ft. installed	$12.5 million
Add Pulse Energization at $6/sq.ft.	$3.42 million
SO_3 System installed - S burner type	$2.8 million

Annual power costs, however, would be much less for the pulse system than for SO_3 conditioning. This is in particular the case for the energy conserving system dealt with here. During operation on medium resistivity dust at 150°C with a collection plate current density of 10 μA per square foot the power supplied from the mains to the DC as well as the pulse unit was measured to about 0.5 watts per square foot of collection plate area. At a price of $0.04/kWh for 7000h operation this is about $80,000.

This shall be compared with annual operating cost of $417,000 for the SO_3 conditioning composed of $210,000 for power to the precipitator and sulfur at $50,000 ($0.032/Tn. coal burned) and incremental maintenance, labor, utilities and overhead of about $157,000.

Other proprietory chemical conditioning systems, where applicable, have very low capital costs, but cost of chemicals may be high - typically $0.3-0.5/Tn. coal burned.

CONCLUSIONS

Full scale field tests with the energy conserving pulse energization system described in the paper have shown that the performance of precipitators collecting high resistivity dust can be improved considerably by pulse energization. The improvement results in capital savings from reduced size requirements for new installations, and in upgraded performance of existing installations.

The tests have demonstrated that the automatic controls of the system are able to maintain a stable operation and to adjust continuously the DC voltage level, pulse peak voltage, and pulse repetition frequency for optimum precipitator performance under the various operation conditions experienced.

Further, a test with continuous operation of a unit for about one year has shown that the equipment has the required degree of reliability for practical application. The pulse energization system is now being manufactured in the United States as well as in Europe.

The practical arrangement of the system gives an easy installation with a high degree of flexibility on new as well as on existing precipitators. The high voltage DC and pulse supplies may be placed on the precipitator roof or at any other suitable location in the vicinity of the precipitator. For old installations the existing DC high voltage supply may be used. The control panels require a dust-free environment and suitable ambient temperatures. If desired, the panels can be placed in a container delivered with the system.

Comparison of installation costs for new precipitators shows that even at medium resistivity levels, where only moderate w_k improvement factors are attained, pulse energization with this system is an interesting alternative to a large precipitator with conventional DC energization.

The advantage is even more pronounced for upgrading of existing precipitators, where the installation costs for additional collection area in an example far exceed the costs of the alternative pulse solution.

In the latter case an SO_3 conditioning system giving a similar enhancement factor as the pulse solution may be installed at somewhat lower costs than for the pulse system.

A comparison of the operating costs for the two solutions, however, shows that pulse energization with the energy conserving pulse energization system can be performed at much lower annual costs than SO_3 conditioning.

REFERENCES

1. Lausen, P.: Improved Precipitation by Pulse Energization. Proc. of US-Japan Seminar on Measurement and Control of Particulates Generated from Human Activities, Nov. 1980, Kyoto, Japan.

2. Joergensen, H.J., J.T. Kristiansen and P. Lausen: Influence on Particle Charging of Electrical Parameters at DC and Pulse Voltages. 3rd Symposium on The Transfer and Utilization of Particulate Control Technology. March 1981, Orlando, Florida, U.S.A.

3. Petersen, H.Hoegh and P. Lausen: Precipitator Energization Utilizing an Energy Conserving Pulse Generator. Proc. of 2nd Symposium on The Transfer and Utilization of Particulate Control Technology. July 1979, Denver, Colorado, U.S.A.

4. Lausen, P.: Energy Considerations on Pulse Energization of Electrostatic Precipitators. Proc. of US-Japan Seminar on Measurements and Control of Particulates Generated from Human Activities, Nov. 1980, Kyoto, Japan.

5. Petersen, H.Hoegh: Electrostatic Precipitators for Cement Mills, Kilns, and Coolers - Control of Operating Conditions During Transition Periods. Presented at IEEE Cement Industry Technical Conference. May 1978, Roanoke, Virginia, U.S.A.

SO_2 REMOVAL BY DRY INJECTION AND SPRAY ABSORPTION TECHNIQUES

By: Edward L. Parsons, Jr.
Buell Emission Control Division
Envirotech Corporation
Lebanon, Pennsylvania 17042

Vladimir Boscak
Chemico Air Pollution Control Corporation
Envirotech Corporation
New York, New York 10001

Theodore G. Brna
Industrial Environmental Research Laboratory
United States Environmental Protection Agency
Research Triangle Park, North Carolina 27711

Ronald L. Ostop
Department of Public Utilities
City of Colorado Springs
Colorado Springs, Colorado 80903

ABSTRACT

The initial phases of EPA-sponsored test programs on dry injection and spray absorption were executed from December 1979 through July 1980 at Buell's Colorado Springs test facilities and established a solid base of process design data. This paper presents the results of EPA-funded follow-up studies completed in October 1980, which addressed issues of waste product disposal for both dry FGD methods, and further explores parametric optimization of the more commercially important spray absorption process.

Representative dry injection and spray absorption waste product samples were subjected to a variety of simulated stabilization and disposal processes and then evaluated for compressive strength, permeability, and leaching characteristics.

Parametric performance tests were run to determine the effects of alkaline fly ash, quenching of absorber inlet gas with water sprays, and hot gas bypass reheat on spray absorption process efficiency. Alternate sorbents such as dolomitic lime, trona, and limestone were evaluated and the effect of adipic acid additive on lime and limestone slurries was tested. All results are compared to data correlations derived from earlier testing.

INTRODUCTION

The technical feasibility of removing SO_2 from flue gases of coal-fired boilers by dry injection and spray absorption techniques has been widely demonstrated in pilot-scale studies. Comparatively little has been published, however, pertaining to waste product characterization and/or environmentally acceptable disposal methods for either process. For dry injection or spray absorption using sodium-based sorbents, successful demonstration of such methods is critically important to the future development of the process, due to the high potential for leaching of sodium salts from landfill disposal sites. The widely proclaimed ease of disposal and stability of the waste product from lime-based spray absorption remains to be proven in scientifically controlled tests. In EPA-sponsored tests conducted at Envirotech's Lebanon R&D laboratory and Battelle's Columbus Laboratories, representative samples of spray absorption and dry injection waste product obtained from Buell's Colorado Springs pilot plant were subjected to various stabilization processes and were evaluated for environmental acceptability in simulated landfill disposal.

With 13 utility systems totaling over 4000-MW capacity on order, spray absorption FGD stands on the threshold of its first generation of large-scale commercial application. However, even as the startup dates for major installations in the 400- to 600-MW class approach, much remains to be investigated in regard to flue gas pretreatment, the effects of ash chemistry, and alternate sorbent types and preparation methods. These and other issues were pursued in an EPA-funded follow-up study completed in October 1980, which was a continuation of the original spray absorption test program conducted by Buell and Anhydro A/S at their Colorado Springs test facility (1). The 2-MW equivalent pilot plant used in both programs was installed in slipstream configuration at the inlet of the 189 m^3/s (400,000 acfm) Buell reverse air filter operating on Boiler No. 6 of the City of Colorado Springs' Martin Drake Station, a 85-MW pulverized coal-fired steam generator burning low-sulfur Northwest Colorado coal.

SPRAY ABSORPTION WASTE PRODUCT STUDIES

Relative ease of handling and disposal of spray absorption waste products is widely claimed as an advantage over wet FGD processes, but is supported by little in the way of published geo-technical data. It does seem reasonable that the mixture of fly ash and calcium salts would undergo pozzolanic reactions after mixing with water and landfilling, rendering the material acceptable from the standpoint of unconfined compressive strength, permeability, and leachability. To confirm this hypothesis, representative samples of lime-based spray absorption waste product from the Colorado Springs pilot plant were tested at Envirotech's R&D laboratory in Lebanon, PA.

Waste product samples were obtained from the absorber and baghouse hoppers for test points representing straight-through (no waste product recycle) operation at a low stoichiometric ratio as well as a high stoichiometric ratio run with 50 percent recycle of the total waste product. The results of chemical analysis of the samples are presented in Table 1 and indicate 20 to 25 percent calcium species for the low stoichiometry case (Sample 1) and 40 to 50 percent for the higher stoichiometry (Sample 2).

TABLE 1. CHEMICAL ANALYSIS OF DRY FGD WASTE PRODUCT FROM SPRAY ABSORPTION PILOT PLANT

	Sample 1 Low Stoichiometry Straight Through		Sample 2 High Stoichiometry 50% Recycle	
Constituent	Percent Weight		Percent Weight	
	Absorber	Baghouse	Absorber	Baghouse
Solids	99.9	99.7	96.8	98.5
$CaSO_3 \cdot 1/2\ H_2O$	3.9	2.3	19.2	20.8
$CaSO_4 \cdot 2\ H_2O$	1.2	2.2	9.3	2.3
$CaCO_3$	10.7	10.7	9.9	11.9
Mg	0.9	1.0	0.2	3.0
Acid Insoluble	80.4	77.5	59.6	62.1

The samples were mixed with varying amounts of water, and simulated landfill specimens were prepared using a Harvard miniature compactor and cured in constant humidity chambers. For the high stoichiometry case, baghouse and absorber waste product samples were prepared separately; for the low stoichiometry case, equal parts of baghouse and absorber waste product were mixed. Specimens were tested for unconfined compressive strength and permeability after two different curing periods. The results of these tests are summarized in Table 2 and show that the highest strength and lowest permeability coincided for all samples: 80 percent solids gave the best results for Sample 1 and 75 percent solids was best for Sample 2. The results indicate ample compressive strength for the support of men and equipment (19.5 tonne/m^2), and the permeability is acceptable ($\lesssim 10^{-6}$cm/sec).

TABLE 2. UNCONFINED COMPRESSIVE STRENGTH AND PERMEABILITY FOR SIMULATED LANDFILL DISPOSAL OF DRY FGD WASTE PRODUCT SAMPLES FROM SPRAY ABSORPTION PILOT PLANT

Percent Solids	70	75	80	85
Compressive Strength, tonne/m^2(ton/ft^2)				
Sample 1 - Mixture of spray absorber and baghouse waste product				
After 7 days	32.8 (3.36)	20.9 (2.14)	39.6 (4.06)	24.0 (2.46)
After 26 days	31.5 (3.23)	54.0 (5.53)	61.7 (6.32)	29.4 (3.01)
Sample 2 - Spray absorber waste product				
After 10 days	--	27.5 (2.82)	19.7 (2.02)	18.1 (1.85)
After 21 days	--	29.7 (3.04)	17.7 (1.81)	11.1 (1.14)
Sample 2 - Baghouse waste product				
After 10 days	--	219 (22.4)	84.0 (8.60)	118 (12.1)
After 21 days	--	284 (29.1)	101 (10.4)	106 (10.9)
Permeability, 10^6cm/s(10^{-6} in./sec)				
Sample 1 - Mixture of spray absorber and baghouse waste product				
After 7 days	60 (24)	25 (9.8)	10 (3.9)	44 (17)
After 26 days	45 (18)	9.3 (3.7)	7.1 (2.8)	18 (7.1)
Sample 2 - Spray absorber waste product				
After 10 days	--	2.3 (0.91)	5.1 (2.0)	9.7 (3.8)
After 21 days	--	2.0 (0.79)	3.4 (1.3)	10 (3.9)
Sample 2 - Baghouse waste product				
After 10 days	--	0.25 (0.10) (0.26)	2.0 (0.79) (0.67)	3.5 (1.4) (1.4)

Table 3 summarizes the results of leachate tests performed on equal mixtures of absorber and baghouse waste product using EPA's extraction procedure (Proposed Rules Part 250 - Hazardous Waste Guidelines and Regulations, Federal Register, Volume 43, No. 243, December 18, 1978). The results show that the levels of mercury approximate the proposed level for hazardous waste, but that the seven other heavy metals are far below the proposed levels. It should be pointed out, however, that the extraction tests were performed on the "as received" dry powder samples which had not undergone pozzolanic (hydraulic cement forming) reactions. Thus, the expected contaminant levels from an actual landfill would be lower.

TABLE 3. LEACHATE ANALYSIS FROM EPA'S EXTRACTION PROCEDURE PERFORMED ON "AS RECEIVED" DRY FGD WASTE FROM SPRAY ABSORPTION PILOT PLANT - MIXTURE OF SPRAY ABSORBER AND BAGHOUSE WASTE PRODUCT

Contaminant	Extract Sample mg/l		Proposed Level mg/l
	Sample 1	Sample 2	
Arsenic	0.012	0.015	0.5
Barium	0.029	0.117	10.0
Cadmium	0.006	0.012	0.1
Chromium	0.009	0.021	0.5
Lead	0.015	0.027	0.5
Mercury	0.017	0.021	0.02
Selenium	0.006	0.016	0.1
Silver	0.001	0.011	0.5

DRY INJECTION WASTE PRODUCT STUDIES

Spent material consisting of fly ash and sodium salts from the dry injection FGD pilot program at Colorado Springs' Martin Drake Station (1,2) was analyzed to establish a cost-effective process for the environmentally acceptable disposal of the waste materials. In this study, Battelle's Columbus Laboratories evaluated the insolubility of sodium salt wastes after treatment. The treatment involved pelletizing the wastes after addition of about 5 percent lime and sintering the pellets at a temperature up to 1000°C (1843°F) while noting SO_2 evolution. Testing of the stabilized pellets as aggregates for leaching and strength characteristics was also performed. Based on these analyses, an optimum process, balancing SO_2 evolution during curing and leaching of salts from the stabilized pellets, was defined and costed. The economic analysis for the waste stabilization process used the premises given in the most recent TVA/EPA report for a typical Upper Great Plains 500-MW power plant (3). This analysis indicates that with pelletization and sintering of the sodium salt wastes the dry injection FGD process has a higher cost per kW than lime-based spray absorption when waste disposal costs are included.

SPRAY ABSORPTION PARAMETRIC TESTS

Pilot Plant Description

The slipstream pilot plant used for the follow-on spray absorption tests was essentially the same as described previously (1), except that a spray system and a powder injection system were added upstream of the absorber for pretreatment of the gas with water sprays and/or injection of additional fly ash. The 3.8-m (12.5-ft) diameter Anhydro spray absorber had a flow capacity of 4.0 m^3/s (8500 acfm) at optimum (10-s) residence time and was equipped with a 30-kW (40-hp) belt-driven Anhydro centrifugal atomizer. Gas from the absorber discharge was directed through ductwork designed to permit reheat by either absorber or preheater bypass gas prior to entering a reverse air fabric filter equipped with full-size (0.305-m diameter x 9.30 m long (1-ft diameter x 30.5 ft long)) Teflon-coated fiberglass filter bags. Lime slurries were prepared using a full-scale commercial package-type lime storage, handling, and slaking system, and recycle slurries were prepared by hand and agitated in a 1325-l (350-gal.) tank. Lime and recycle slurries were circulated to their points of application by independent flooded loops, and the process flow of each slurry was automatically controlled by a variable speed progressing cavity slurry pump. An SO_2 vaporizing and injection system enabled spiking the slipstream gas flow up to a level of 2500 ppm SO_2, and a water-cooled heat exchanger allowed slipstream gas precooling by as much as 44°C (80°F). The pilot plant was fully instrumented to measure SO_2 concentrations, gas and slurry flow rates, temperatures, and pressures. All instrument channels were scanned, data were converted to engineering units, and all data were printed on both an instantaneous and time-averaged basis by a Monitor data logger.

Alkaline Fly Ash

Since the Martin Drake Station burns a northern Colorado coal with low available alkalinity when slurried (0.4 to 0.6 percent expressed as $Ca(OH)_2$), the effect of alkaline ash could be investigated only by introducing such ash into the slipstream gas flow. A supply of moderately alkaline Texas lignite ash was obtained from the Monticello Station of Texas Utilities Services to study the effect of ash alkalinity. The available alkalinity of this ash when slurried is about 2.5 percent alkalinity (expressed as $Ca(OH)_2$). The total alkaline content of this ash is given in Table 4.

The alkaline fly ash was pneumatically injected into the slipstream flow upstream of the absorber at a rate of 0.080 kg/m^3 (3.5 gr/ft^3) of flue gas. Performance tests were run at various approaches to saturation temperature at the absorber outlet, with and without waste product recycle, to assess the impact of ash alkalinity. In Figure 1, the results of these tests are compared with the lime data obtained with nonalkaline ash in the original spray absorption test program (1). Since the FGD reactions in lime-based spray absorption take place only in an aqueous medium, the alkaline ash would be expected to have little or no effect on straight-through performance. This is borne out by Figure 1. For the same reason, recycle performance is noticeably better than without recycle because utilization of ash alkalinity made available in the recycle slurry provides a benefit over a nonalkaline ash.

TABLE 4. ANALYSIS OF TEXAS LIGNITE ASH FROM TEXAS UTILITIES SERVICES' MONTICELLO STATION

Component	Percent Weight	Component	Percent Weight
SiO_2	60.05	K_2O	0.89
Al_2O_3	21.91	Li_2O	0.02
Fe_2O_3	3.09	CaO	8.87
TiO_2	1.61	MgO	2.04
P_2O_5	0.10	LOI*	0.10
SO_3	0.31	Undetermined	0.55
Na_2O	0.46		

*Loss on Ignition

Absorber Inlet Prequench

Diffusion of SO_2 into the sorbent droplets was shown to be rate-controlling for SO_2 removal across the absorber (1). Since SO_2 must diffuse counter to water vapor evolving from the droplet surface, greater SO_2 mass transfer would be expected if the initial water evaporation rate could be retarded. Prequenching the absorber inlet gas flow with water sprays would reduce the initial driving forces for the evaporation rate as decreased temperature of the flue gas gives a lower gas-liquid temperature differential, while higher gas moisture reduces the vapor pressure-partial pressure differential. Both of these forces tend to reduce the evaporation rate. However, prequench reduces the percent of total water evaporated which passes through the absorber atomizer in the process, and since there is an upper limit on the solids concentration which can be used for lime and recycle slurries, the ability of the system to utilize recycle is effectively reduced. Thus for a net benefit, prequench must more than balance the loss of recycle capacity it entails.

Performance tests were run using a spray system to prequench the absorber inlet gas from its normal temperature of about 163 to 149°C (325 to 300°F) and 135°C (275°F) by means of water sprays. The results of these tests are compared to the lime data in Figure 2, which indicate only a very slight benefit due to prequench at 135°C (275°F), well within the "noise" level of the data. Since about 25 percent of the total water must be diverted to the sprays to get the 135°C (275°F) temperature, the capacity to recycle is seriously reduced. Thus, it appears that prequench offers no advantage to the spray absorption process.

Lime With Adipic Acid Additive

Adipic acid was tested as a means of increasing the rate of dissolution of $Ca(OH)_2$ in the lime slurry and thus improving SO_2 removal. The results of tests conducted with 1500 and 3000 ppm adipic acid in the lime slurry are compared to the lime data in Figure 2. A significant benefit was realized only with recycle and 3000-ppm adipic acid. A greater effect would be expected with recycle since recovery of residual adipic acid in the waste product will increase the total adipic acid concentration in the slurry system. It is also reasonable to suppose that a sufficiently high level of adipic acid will reduce the recycle slurry pH to the level where alkalinity in the waste product will have increased availability. The level of benefit shown merits further investigation of the effect of adipic acid on the lime-based spray absorption process, including cost impacts.

Dolomitic Lime

In some spray absorption applications, particularly in the Northeast, a dolomitic lime may be more readily available than high calcium lime, and thus would be desirable as a sorbent, provided that reasonable performance was obtainable. This would be a problem with most sources of dolomitic lime, since magnesium oxide is usually "hard-burned" in the calcining process, and therefore will not explosively slake to form the highly reactive lime slurry needed for best results in spray absorption FGD. A commercial soft-burned dolomitic lime was used in the tests described here.

Dolomitic lime requires special slaking methods because of the unusual slaking characteristics of MgO. Slaking water must be preheated to 77°C (170°F) to obtain the optimum slaking temperature range of 88 to 93°C (190 to 200°F) at a water-to-lime ratio of 4:1, and slaker residence time must be extended to at least 30 minutes to allow a complete slaking reaction to occur. Under these optimum conditions, an extremely thixotropic lime slurry is produced which requires about double the agitator power of a normal lime slurry of the same solids concentration. The results of a straight-through performance test are compared with the lime data base in Figure 3 and indicate performance essentially equivalent to high calcium lime for a 11 to 17°C (20 to 30°F) approach to saturation at the absorber outlet. Due to the hydroscopic nature of the magnesium sulfites and sulfates in the waste product, a minimum approach to saturation of 14°C (25°F) is recommended to obtain dry powder. It is emphasized that these results were obtained with a soft-burned dolomitic lime and that the normal hard-burned variety would likely produce less satisfactory results.

Limestone with Prequench and Adipic Acid

Further attempts were made in this test program to improve the poor SO_2 removal results obtained in the original test program with limestone slurries. Differing concentrations of adipic acid, recycle of waste product, and prequench were all tried with disappointing results. The best performance results for 200 to 500 ppm SO_2 at the absorber inlet and a 14°C (25°F) approach are plotted in Figure 4. These data show that SO_2 removal is severely rate-limited by the slow reaction with $CaCO_3$ and thus increasing stoichiometry has little or no effect on SO_2 removal. Further tests were run at 1000 ppm SO_2 with worse results. The highest SO_2 removal was observed at the lowest SO_2 concentration (214 ppm), which further confirms that reactions with $CaCO_3$ are rate-limiting.

Trona

Attempts were made to improve the trona results presented earlier (1) by means of partial recycle of the waste product. Due to the very high reactant utilization, little or no performance improvement was achieved.

Hot Gas Bypass Reheat

Reported test results (1) establish the importance of operating at an exit gas temperature from the spray absorber as close as possible (about 11°C (20°F)) to the adiabatic saturation temperature to attain the optimum SO_2 removal efficiency. Yet, many spray absorption system specifications require baghouse inlet temperatures as much as 44°C (80°F) higher than saturation temperature. Hot gas bypass reheat is often the most cost-effective means of accomplishing the reheat but entails the loss of SO_2 removal efficiency due to bypassing part of the flue gas around the absorber. For reheat up to about 28°C (50°F) above the saturation temperature, this is the only penalty paid for reheat as the percentage SO_2 removal across the baghouse is essentially unchanged. Higher levels of reheat, however, reduce SO_2 removal in the baghouse as well and, thus, impose a double penalty. With reheat of 42 to 47°C (75 to 85°F) above saturation, the baghouse flange-to-flange SO_2 removal percentage is reduced to 20 percent of the value which would be experienced with no reheat. Apparently, the extreme degrees of reheat dry out the residual moisture in the sorbent particles leaving the absorber to the point that the reaction rate with SO_2 in the filter cake is substantially reduced.

CONCLUSIONS

The series of follow-up tests described in this paper was undertaken to resolve issues of waste product disposal and process optimization. A technically feasible, although economically unattractive, disposal method was demonstrated for dry injection waste product, and the applicability of conventional fly ash disposal methods to spray absorption waste product was confirmed. Alkaline fly ash was found to have a beneficial effect on spray absorption process efficiency when recycle was used. Soft-burned dolomitic pebble lime was found to be an acceptable reagent if the special requirements for its use can be met. Adipic acid additive to lime slurry was found to improve performance when used at the 3000-ppm level and with waste product recycle. Prequench of the absorber inlet gas with water spray was found to be relatively ineffective in improving SO_2 removal with either lime or limestone sorbent. The low levels of performance for limestone sorbent reported earlier were not improved by recycle, higher stoichiometry, or higher levels of adipic acid additive. Recycle tests with trona sorbent failed to improve upon results previously observed for straight-through operation.

ACKNOWLEDGEMENT

The authors acknowledge with appreciation the contributions of Edward Tomeo, James Utt, and Thomas Griffen of Buell/Envirotech, and Fritz Paulsen of Anhydro A/S for their assistance in the collection and reduction of the data presented here. This work was supported under EPA Contract No. 68-02-3119, Mod. 3 and with the cooperation of the City of Colorado Springs.

REFERENCES

1. E. L. Parsons, Jr., L. F. Hemenway, O. T. Kragh, T. G. Brna, and R. L. Ostop, "SO_2 Removal by Dry FGD," presented at the U.S. Environmental Protection Agency's Sixth FGD Symposium, Houston, TX, October 1980.

2. D. A. Furlong, T. G. Brna, and R. L. Ostop, "SO_2 Removal Using Dry Sodium Compounds," presented at the AIChE 89th National Meeting, Portland, OR, August 1980.

3. T. A. Burnett, K. D. Anderson, and R. L. Torstrick, "Spray Dryer FGD: Technical Review and Economic Assessment," presented at the U.S. Environmental Protection Agency's Sixth FGD Symposium, Houston, TX, October 1980.

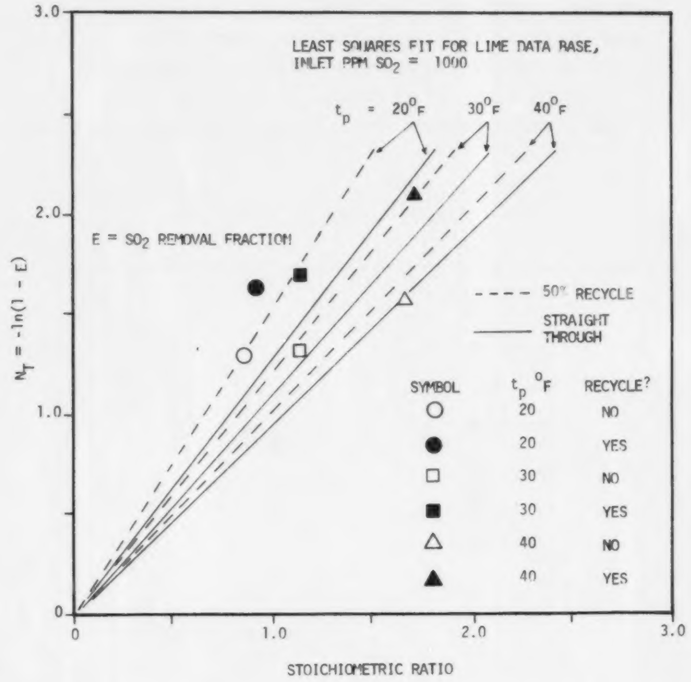


Figure 1. Comparison of SO_2 removal data for lime with injection of 3.5 gr/ACF alkaline ash (see Table 4) with lime data base, at different values of approach temperature, t_p. All data for 1000 ppm SO_2 at inlet and 10 second residence time.

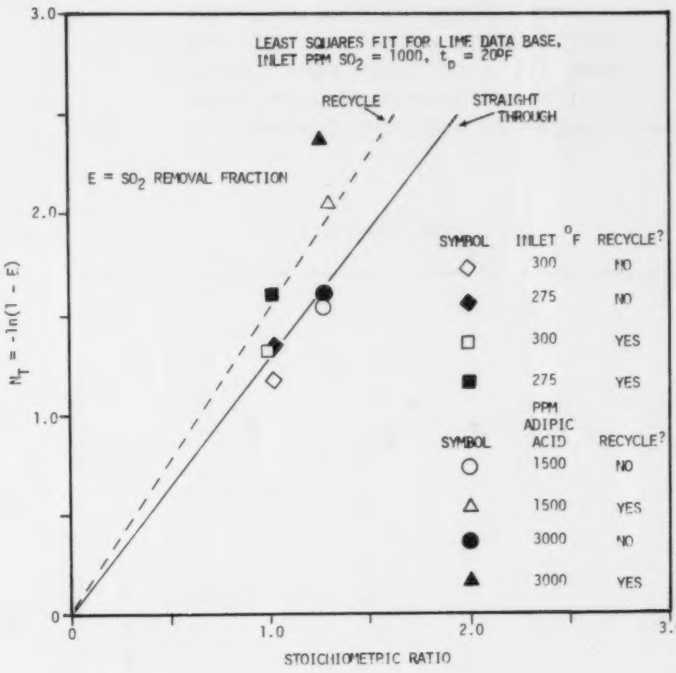


Figure 2. Comparison of SO_2 removal for lime with prequench, recycle and adipic acid additive to lime data base. All data for 1000 ppm SO_2 at inlet, approach temperature, t_p = 20°F, and 10 second residence time.

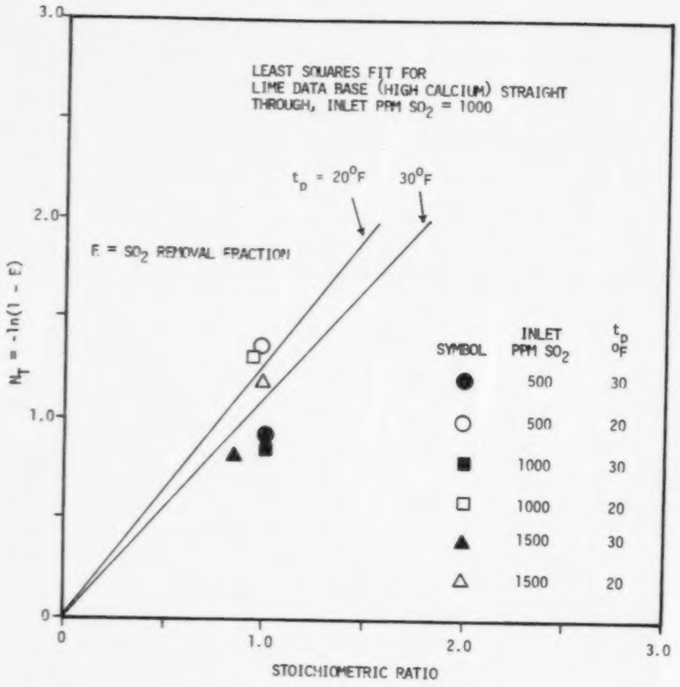


Figure 3. Comparison of SO_2 removal data for soft-burned dolomitic lime with high calcium lime data base, with approach temperature, t_p = 20°F and 30°F. All data for straight through operation and 10 second residence time.

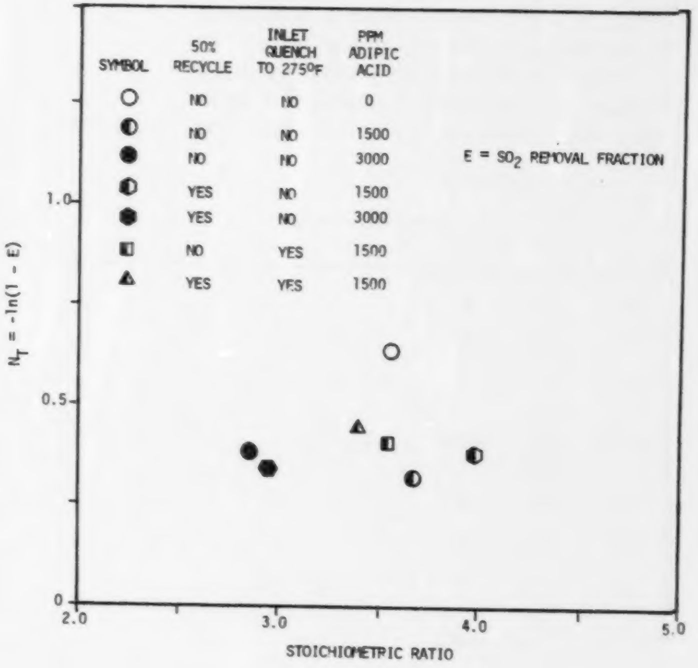


Figure 4. SO_2 removal data for Q4 grind limestone with prequench, recycle, and adipic acid additive. All data for 200 to 500 ppm SO_2 at inlet and 10 second residence time. Approach temperature, t_p = 25°F.

DRY SCRUBBING SO_2 AND PARTICULATE CONTROL

By: Nicholas J. Stevens
Ghassem B. Manavizadeh
George W. Taylor
Michael J. Widico

Research-Cottrell, Inc.
Somerville, New Jersey 08876

ABSTRACT

In dry SO_2 scrubbing, the spray dryer and fabric filter are employed to a significant extent for both SO_2 removal and particulate solids collection. Pilot test results were obtained on low sulfur fuels to elucidate the roles of each control device in the dry scrubbing system.

SO_2 removal in the spray dryer and fabric filter is compared and the important process variables identified. Particulate collection of fly ash/FGD solids mixtures by the spray dryer and fabric filter is examined. The relative amounts of solids collected at different operating conditions are presented. Fabric filter pressure drop variation with time and the effect of dry scrubbing solids on the specific resistance coefficient are described. Spray dryer and fabric filter solids are examined for particle size distribution, chemical composition and moisture content.

For Presentation at the U.S. EPA Third Symposium
on the Transfer and Utilization of
Particulate Control Technology

Orlando, Florida
March 9-12, 1981

TEXT

The spray dryer is the primary SO_2 control element while the fabric filter is the primary particulate control unit. This paper presents the extent and limits of each device for SO_2 and particulate removal based on the results of field pilot test programs.

Pilot Plant Description

The pilot test system (See Figure 1), designed to treat up to 10,000 ACFM[1] of flue gas, consists of a spray dryer followed by a fabric filter. Dirty flue gas containing SO_2 and flyash continuously enters the top of the spray dryer where it is intimately contacted with finely atomized lime slurry.

Flue gas from the spray dryer enters the bottom of the fabric filter unit and leaves from the top. From the fabric filter, the flue gas flows to an I.D. fan and then to the stack. The induced draft fan moves the treated flue gas through the system and a second "reverse air" fan periodically cleans solids from the fabric filter cloth.

Spray Dryer

The pilot spray dryer is an 8'Ø x 35' high unit equipped with a variable speed rotary disc atomizer. Intimate contact between finely atomized lime slurry and SO_2 in the flue gas and large interfacial area produced by atomization in the spray dryer result in very rapid SO_2 absorption. In the pilot unit, coarse solids tend to settle in the conical bottom of the dryer and are discharged through a rotary valve to receiving drums. The scrubbed flue gas containing finer particles leaves the dryer through a side exit port and flows to the fabric filter.

Temperature drop across the spray dryer is controlled by total water flow to the unit. Water for temperature control is metered as a trim water flow to a mixing tee immediately upstream of the spray dryer atomizer. Increasing lime reagent flow increases the SO_2 removal efficiency at a given water flow, gas flow and sulfur dioxide content. System SO_2 responses to changes in stoichiometry are measured by a duPont UV analyzer which samples both inlet and outlet streams from the spray dryer and fabric filter.

Fabric Filter

The fabric filter unit size is 10' x 15' x 55' and it contains two-sixteen bag compartments each designed to process about 5,000 cfm of flue gas. Each of the fabric filter bags is of commercial utility dimensions, 12" Ø x 30' high, and contains about 94 ft^2 of bag surface.

During an operating cycle, a thin layer of solid particles containing unreacted lime continually builds up on the surface of the filter bags. Flue gas from the spray dryer with a reduced SO_2 concentration flows through the bed of finely divided solids. SO_2 removal occurs although the gas contact time in the bed is short.

---

[1] EPA policy is to express all measurements in Agency documents in metric units. This paper uses English units which are customary in the U.S. to improve clarity of presentation. Conversion factors are provided in the Appendix.

To limit pressure drop across the filter bags resulting from the accumulation of collected solids, a flow of air periodically is passed through the bags in the reverse direction for a short period of time (one-two minutes per hour). The "reverse air" flow causes most of the solids deposited to dislodge from the bag surface and drop into the collection hopper where they are discharged through rotary valves. (During the brief bag cleaning period, flue gas is bypassed around the fabric filter.)

When high SO_2 removal is desired, reagent use becomes excessive unless solids recycle is practiced. These recycle solids are obtained from the baghouse and/or spray dryer and contain unreacted lime. The solids are fed into the recycle tank where they are reslurried with process water. Slurry from the recycle tank is combined with the slaked lime slurry and the mixture is metered into the spray dryer atomizer.

Relative SO_2 Removal

SO_2 removal in the dry scrubbing system is strongly influenced by a limited number of process variables. Stoichiometric ratio (S.R.) and temperature are two of the more significant parameters that dictate SO_2 removal both in the spray dryer and in the fabric filter. The spray dryer, however, is the key SO_2 removal device in the dry scrubbing system. At the conditions tested in the pilot plant, at least 75% of the total SO_2 removal in the dry scrubbing system is accomplished in the dryer, according to Figure 2.

As Figure 2 indicates, a decreasing percentage of the total SO_2 removal takes place in the spray dryer as stoichiometry is increased. Of course, combined SO_2 removal in the spray dryer/fabric filter system is greater at higher stoichiometry. At lower values of S.R. ($\leq$1.0 moles slaked lime/mole SO_2 in), lime utilization tends to be higher in the spray dryer because lime becomes the limiting reagent. A greater fraction of SO_2 removal takes place in the spray dryer at lower S.R. values since relatively little lime reagent is present in the FGD solids to the fabric filter from the spray dryer. At higher S.R., more unreacted lime is conveyed to the fabric filter and is available for reaction because utilization is lower in the spray dryer.

Figure 2 shows that relative SO_2 removal is affected significantly by the spray dryer and fabric filter operating temperatures. Lower operating temperature results in greater SO_2 removal in both the spray dryer and fabric filter. As the fabric filter operating temperature is decreased between 200°F and 145°F, SO_2 removal in the fabric filter increases significantly and relative SO_2 removal shifts toward the fabric filter.

SO_2 removal in the spray dryer is favored by keeping the atomized lime slurry as wet as possible for as long as possible. Lower operating temperature produces improved SO_2 removal but results in a moist solids product that is difficult to discharge from the spray dryer bottom. The optimum spray dryer operating temperature is arrived at by striking a balance between high SO_2 removal and smooth handling of moisture-laden product solids. But, the fabric filter operating temperature often must be controlled at a higher level than that of the spray dryer. Avoidance of dew point problems (condensation), bag blinding and low buoyancy conditions in the stack are common reasons for increasing the fabric filter operating temperature. As a consequence, relatively less SO_2 removal takes place in the fabric filter under these conditions.

SO_2 Removal vs. Pressure Drop

Fabric filter SO_2 removal varies not only with the key process variables, stoichiometric ratio and temperature, but also with time between cleaning cycles. After reverse air cleaning of the filter bags, fabric filter pressure drop (Δp) and SO_2 removal increase with time. Figure 3 presents SO_2 removal in the fabric filter as a function of the Δp increase during different operating cycles. Percent SO_2 removal initially tends to increase linearly with pressure drop and then begins to level off at higher ΔP values near the end of the cleaning cycle. In these runs, pressure drop increased from about 2.0 in. H_2O initially to between 4 and 5 in. H_2O at the end of operating cycles of 60-90 minutes duration.

Figure 3 also shows the strong effects of stoichiometric ratio and fabric filter inlet temperature on $\%SO_2$ removal in the fabric filter. Percentage removals of SO_2 entering the fabric filter vary from as low as 20-30% at S.R. = 1.0 and an inlet temperature of 175°F to as high as 60-70% at S.R. = 2.25 and a temperature of 155°F. Figure 3 indicates that reducing the fabric filter inlet temperature from 175°F to 155°F has at least as great an effect on $\%SO_2$ removal as increasing S.R. from 1.0 to the range of 2.1 to 2.25.

Fly Ash vs. FGD Solids

The relative amounts of fly ash and FGD solids in the mixture collected in the spray dryer and fabric filter depend primarily on three factors:

1. Fly ash grain loading in the flue gas entering the dry scrubbing system
2. SO_2 concentration of the flue gas
3. Lime stoichiometric ratio

Fly ash grain loadings of 1.0-2.5 grains/actual cubic foot (dry) were measured in the flue gas at both Big Brown (TUSI) in Texas and at Comanche Station (P.S. of Colorado) in Colorado. The amount of FGD solids collected is directly related to the arithmetic product of the incoming flue gas SO_2 concentration and the lime stoichiometric ratio used in a particular run to remove SO_2. SO_2 levels experienced varied from 200 to 2000 ppm while stoichiometric ratios tested ranged from about 0.5 to 6.0 moles slaked lime/mole SO_2 fed to the spray dryer.

For a given stoichiometry, the amount of FGD solids on a weight basis depends on the extent of conversion of lime to sulfur products, i.e., reagent utilization, during dry SO_2 scrubbing. The weight of FGD solids collected is also slightly affected by the lime converted to calcium carbonate by reaction with CO_2 and by the degree of oxidation that occurs. The extent of the oxidation reaction determines the ratio of calcium sulfite to calcium sulfate found in the product solids. The sulfite/sulfate ratio of the product solids in dry SO_2 scrubbing is significantly greater than is generally found in wet FGD scrubbing. The larger ratio indicates that considerably less oxidation occurs in the dry scrubbing systems where conditions are not as favorable as in wet FGD systems. Table 1 shows typical chemical compositions of product solids collected from the spray dryer and fabric filter under recycle and lime-only dry scrubbing operations.

TABLE 1. TYPICAL PRODUCT SOLIDS CHEMICAL COMPOSITIONS
(Weight %)

Component	R-425 (Recycle)		R-501R (Lime Only)	
	SD	FF	SD	FF
$CaSO_3 \cdot 1/2\ H_2O$	18.6	21.0	23.9	23.0
$CaSO_4$	6.7	10.5	4.8	4.9
$Ca(OH)_2$	0.5	<0.1	<0.1	1.3
$CaCO_3$	8.7	6.7	17.5	13.2
Flyash	65.5	61.7	53.7	57.6
	100.0	99.9	100.0	100.0

Product Solids

The product solids collected in the spray dryer are coarser than those collected in the fabric filter. Table 2 shows the mean particle diameter and the geometric standard deviation of spray dryer and fabric filter solids obtained from pilot plant runs at a number of different conditions. From the runs, the average mean particle diameter (50 wt.% solids less than the mean value) of the spray dryer solids is about 30-35 microns and the average for fabric filter solids is about 10 microns. Figure 4 presents typical particle size distributions of solids collected in the spray dryer and fabric filter. As Figure 4 also shows, the fabric filter fly ash/FGD solids particle size in this case is nearly identical to that of fly ash itself. The relative difference in particle size of the spray dryer and fabric filter solids is illustrated by the selected scanning electron micro (SEM) photographs of Figures 5 and 6. For comparison, fly ash particulate is depicted in Figure 7.

TABLE 2. TYPICAL PRODUCT SOLIDS PARTICLE SIZES

	Spray Dryer		Fabric Filter	
Run No.	Mean	Std. Dev.	Mean	Std. Dev.
	(Microns)		(Microns)	
105	35.0	3.2	8.1	2.8
106	26.2	3.2	9.8	2.9
115	42.5	3.5	6.8	2.5
130	19.0	3.6	11.0	3.3
603	35.0	4.2	6.2	3.1
928	39.0	5.0	14.0	4.0
Average	32.8	3.8	9.3	3.1

Spray dryer solids, according to Figure 5, tend to be composed of a mixture of large discrete particles, as well as agglomerates of flyash and FGD solids. From Figure 6, fabric filter solids are made up of finer individual particles and smaller agglomerates. Particulate size and the tendency to agglomerate appear to be related to the moisture content of the solids collected. Figure 8 shows that the percentage of the total solids collected in the system that drops out in the spray dryer increases directly as the moisture content of the spray dryer solids increases. In normal operation, spray dryer solids contain more moisture (10-25 wt.%) than fabric filter solids (<5 wt.%).

As Figure 1 shows, the flue gas and particulate leaving the spray dryer must turn essentially 180° in direction in order to enter the outlet duct located near the bottom of the spray dryer. In turning, the larger, more agglomerated solids tend to collect in the spray dryer hopper while the finer particles are carried by the flue gas into the fabric filter.

Additional solids drying occurs between the time the flue gas leaves the spray dryer and its particulate is collected in the fabric filter hopper. It is likely that the additional drying causes some agglomerates to disintegrate and results in the collection of finer particulate in the fabric filter.

Fabric Filter Pressure Drop

Particulate collection in the fabric filter during dry SO_2 scrubbing produces an accumulation of the flyash/FGD solids mixture on the filter cloth with time during an operating cycle. Figure 9 shows typical linear pressure drop increases as a function of time during the cycle for Big Brown fly ash alone and for mixtures of fly ash and FGD solids. Dry scrubbing system operation with lime slurry feed, but with no recycle, produces about the same rate of pressure drop increase vs. time as operation with fly ash alone. The pressure drop buildup rate is comparable in the two cases even though the grain loading in the runs containing FGD solids is nearly double that present in the fly ash-only run (4.6 vs. 2.5 gr/acf). When recycle solids are introduced into the system, in addition to the lime slurry feed and fly ash already present in the flue gas, a significantly greater increase in pressure drop with time is experienced. In this case under recycle conditions, the total particulate grain loading in the system approaches twice that encountered in the lime-only, no-recycle run (7.9 vs. 4.6 gr/acf), and more than three times greater than that for the fly ash-only run.

Specific Resistance Coefficient

Specific resistance coefficients computed from pressure drop vs. time data show that the fabric filter cake resistance decreases as the FGD solids content in the fly ash/FGD solids mixture increases. Figure 10 presents a correlation of the specific resistance coefficient, k_2, versus the slaked lime content fed to the spray dryer/fabric filter system. Values of k_2 range from about 30 in. H_2O-min.-ft./lb. for fly ash alone to as low as 5 in. H_2O-min.-ft./lb. as the lime grain loading is increased up about 3.5 gr/acf or 5×10^{-3} lbs. slaked lime/acf. of flue gas fed to the fabric filter. In these runs, the lime grain loading is directly proportional to the stoichiometric ratio used since the SO_2 concentration in the inlet flue gas to the system was held constant at 800 ppm.

The effect of lime grain loading appears to be more important in determining the specific resistance coefficient than the total grain loading or the recycle solids grain loading. For example, k_2 decreased from about 15 in. H_2O-min.-ft./lb. in the recycle runs to near 5 in. H_2O-min.-ft./lb. in the lime-only test run at high lime grain loadings, although the total particulate grain loadings were approximately the same. The fly ash grain loading entering the dry scrubbing system in the flue gas was constant at 2.5 gr/acf. in all runs but the recycle solids and lime grain loadings varied considerably from run to run.

From these results, it appears that a specific resistance coefficient of about 15 in. H_2O-min.-ft./lb. is experienced in the fabric filter operation when Big Brown fly ash is utilized over a fairly wide range of practicable operating conditions for dry SO_2 scrubbing.

ACKNOWLEDGEMENTS

We thank the host utilities, Public Service of Colorado (Comanche Station) and Texas Utilities (Big Brown Station), and their employees for the help and cooperation in enabling Research-Cottrell to conduct the pilot test programs. We also wish to thank Dr. Theodore G. Brna, EPA Project Officer, for his aid and direction in conducting the EPA-funded portion of the work reported in this paper.

APPENDIX

CONVERSION FACTORS

To Convert From English	To Metric	Multiply By
scfm (60°F)	nm^3/hr (0°C)	1.61
cfm	m^3/hr	1.70
°F	°C	(°F-32)/1.8
ft	m	0.305
gr/scf	gm/m^3	2.29
in.	cm	2.54
in. H_2O	mm Hg	1.87
lb	gm	454

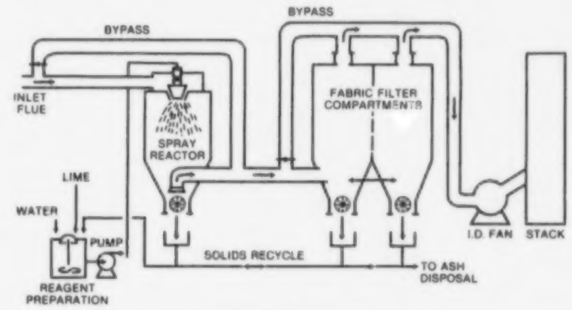

BYPASS
BYPASS
INLET FLUE
SPRAY REACTOR
FABRIC FILTER COMPARTMENTS
LIME
WATER
PUMP
REAGENT PREPARATION
SOLIDS RECYCLE
TO ASH DISPOSAL
I.D. FAN
STACK

FIGURE 1 RESEARCH-COTTRELL DRY SCRUBBING PILOT FLOW DIAGRAM

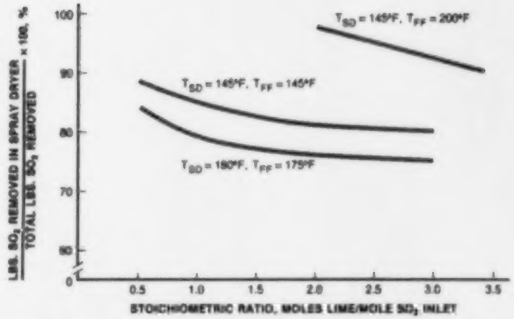


FIGURE 2 RELATIVE SO$_2$ REMOVAL

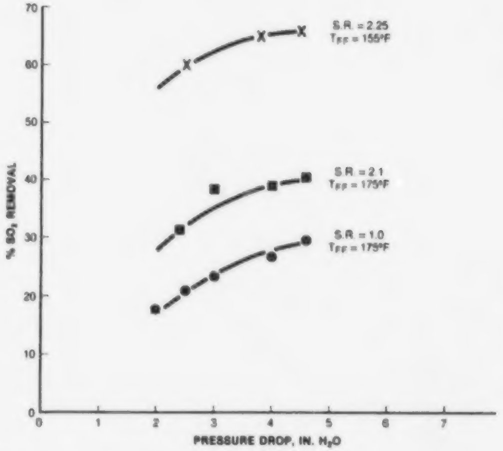


FIGURE 3 FABRIC FILTER SO$_2$ REMOVAL

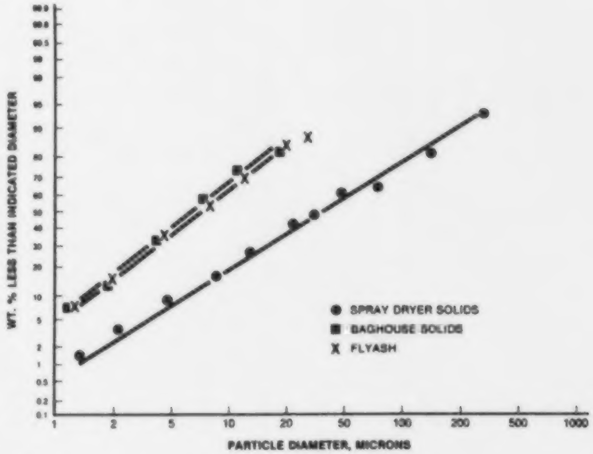


FIGURE 4 PARTICLE SIZE DISTRIBUTIONS

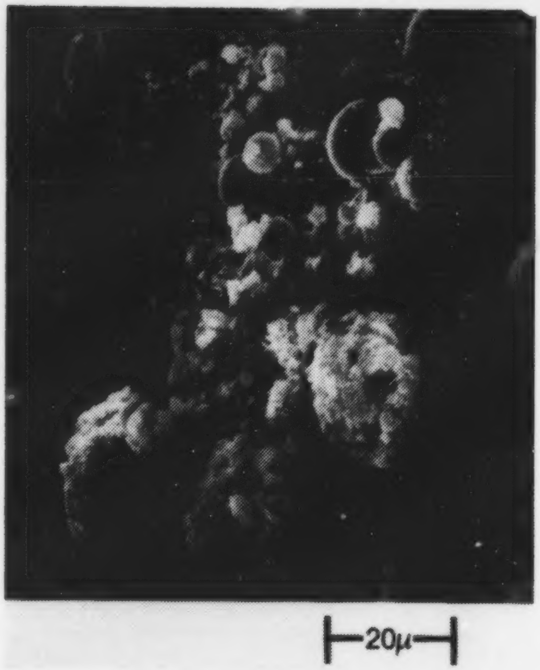


FIGURE 5 **SPRAY DRYER PRODUCT SOLIDS**

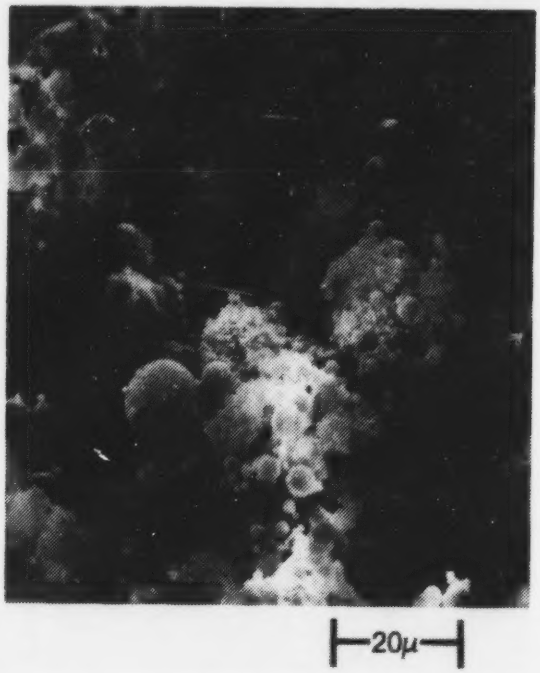


FIGURE 6 **FABRIC FILTER PRODUCT SOLIDS**

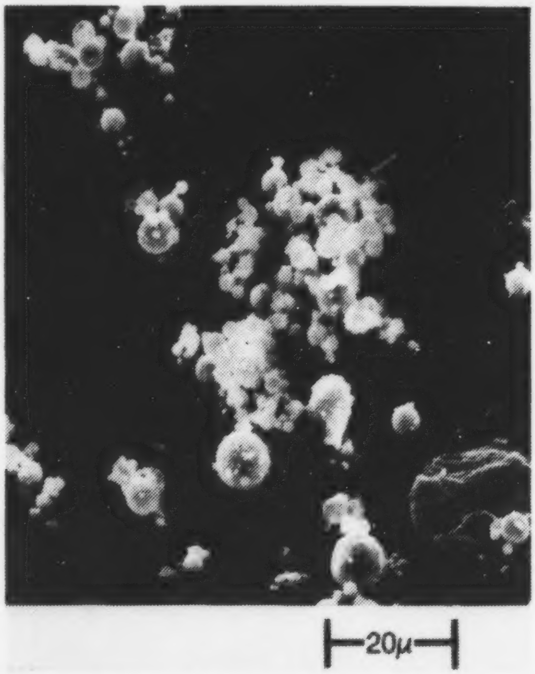


FIGURE 7 **P-C FLY ASH**

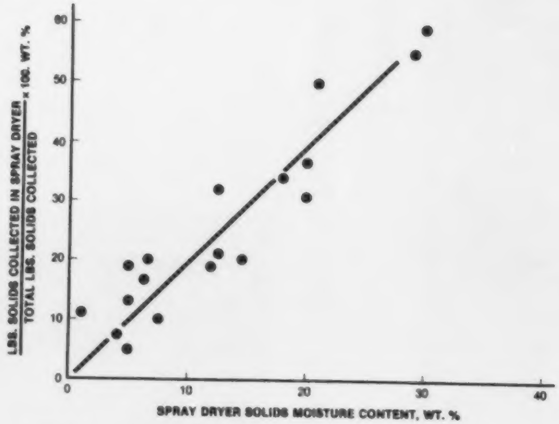


FIGURE 8 **RELATIVE PRODUCT SOLIDS COLLECTION**

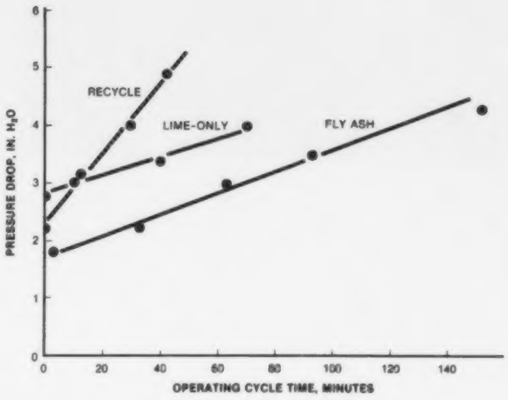


FIGURE 9 **FABRIC FILTER PRESSURE DROP**

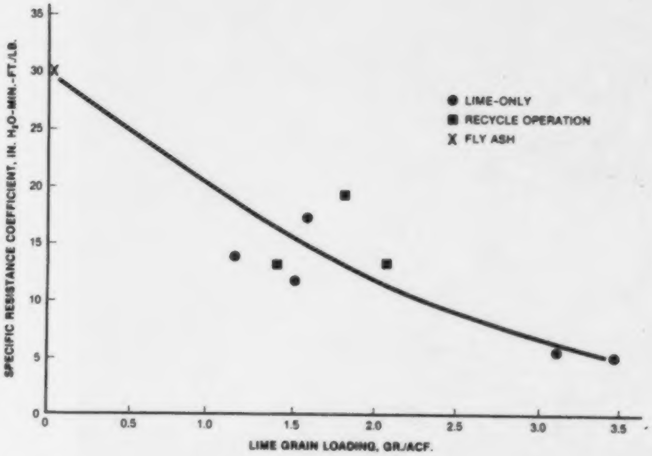


FIGURE 10 **EFFECT of LIME CONTENT on K_2**

FIBER AND FABRIC ASPECTS FOR SO_2 DRY SCRUBBING BAGHOUSE SYSTEMS

By: Lutz Bergmann, V.D.I.
President, Filter Media Consulting, Inc.
P. O. Box 2189
LaGrange, Georgia 30241

SUMMARY/ABSTRACT

For more than 5,000 MW generating capacity (Table 1) - foremost in the utility industry - orders are placed for a relatively new technology in the particulate/SO_2 pollution control field. This technology offers many aspects to the heart of these systems, the filter fabric handling the collection of the combined product. This paper addresses some basic and more specific aspects of the fibers and the fabrics already used and to be selected in future installations.

PREFACE

Economically, SO_2 dry scrubbing systems offer distinct advantages - at least under certain conditions - not only in initial capital investment, but more importantly, in operating and maintenance.(1) Some major differences or a comparison between wet and dry systems may be summarized:

1. A dry SO_2 scrubber has less equipment than a wet scrubber. No equipment such as thickness, centrifuges, vacuum filters, and mixers is required to handle the waste product.

2. Waste products from the dry scrubber are collected along with fly ash and can be handled with conventional dry material handling systems.

3. Scaling and plugging problems due to wet/dry interface are not expected with a dry system since the interface is a point in space. Only dry powder strikes the vessel walls (theoretically).

4. Pilot plant work has indicated that corrosion problems are not experienced in dry systems provided the spray dryer outlet temperature is maintained at a proper level.

5. The dry system has flexibility of operation. Feed rates can be immediately adjusted with little concern for pH control. Reagent consumption closely follows inlet SO_2 concentration.

6. The first cost of the dry system is considerably less than a comparable specified wet scrubbing system.

7. Considerably fewer operators and maintenance personnel will be required for a dry system.

8. The dry system is expected to use only 25% to 50% of the energy required for a wet system.

9. The gas volume of the spray dryers are reduced below those leaving the air heater with the resulting savings and costs for particulate collection equipment.

10. With a dry system, the ID fan can be safely located just ahead of the stack without fear of fan corrosion and imbalance, and without need for reheating.

11. The water requirements for a dry system are much less than for a wet system.

12. Although the process of dry scrubbing is new, the components of the system have substantial operating experience with high availability of plants throughout the world.

13. Sludge disposal is nonexistent and consequently impact on environmental aspects is considerably reduced in utilizing dry systems.

(From Vendor Literature)

TABLE 1. COMMERCIAL SPRAY-DRYER FGD SYSTEMS

Installation	Size MW	Fuel Type, % S	%SO_2 Removal	Alkali Material	Startup Date	Vendor
UTILITY BOILER						
Coyote Unit 1	410	Lignite, 0.78	70	Soda Ash	4/81	RI/WF
Antelope Valley Unit 1	440	Lignite, 0.68	62/78	Lime	4/82	Joy/Niro
Laramie River Unit 3	575	Subbituminous, 0.54	85	Lime	4/81	B&W (ESP)
Stanton Unit 2	63	Lignite, 0.77	73	Lime	9/82	RC
Springerville Unit 1 & 2	350	Subbituminous, 0.69	61	Lime	2/85 9/86	Joy/Niro
Rawhide Unit 1	250	Subbituminous, 0.28	70	Lime	12/83	Joy/Niro
Riverside Unit 6 & 7	100	Blend, subbituminous, bituminous, petroleum coke	70	Lime	9/80	Joy/Niro
Sunflowers Holcomb Unit 1	300	Subbituminous	80	Lime	4/83	Joy/Niro
Niagara Power Tonawanda, NY	100			Soda Ash	82	(ESP)
Colorado Ute, Craig St. #3	450	8950 Btu/lb., 0.70	87	Lime	4/83	B&W (ESP)
Tuscon Elec. Po. Springville Unit 1 & 2	350	Subbituminous, 0.53 - 0.69	61	Lime	84/86	Joy/Niro
Platte River Rawhide #1	250	Subbituminous, 1.3	80	Lime	83	Joy/Niro
Antelope Valley Unit 2	440	Lignite		Lime		Joy/Niro
Light & Power Marquette	44		80	Lime	10/82	Buell/Anhydro
INDUSTRIAL BOILER						
Strathmore Paper Company	14	Bituminous, 2 - 2.5	75	Lime	6/79	Mikropul
Celanese Corp.	22	Bituminous, 1 - 2	70/80	Lime	1/80	RI/WF
University of Minnesota	83	Subbituminous, 0.6 - 0.7	70	Lime	9/81	Carborundum
Calgon Corp. Pittsburgh		1.0 - 2.0 Sulphur +HCl	75	Soda Ash	6/81	Joy/Niro
Argone National Lab.	22			Lime		Joy/Niro

RI/WF - Rockwell International/Wheelabrator-Frye; Joy/Niro - Western Precipitation Div. of Joy Manufacturing CO/Niro Atomizer Inc.; B&W - Babcock and Wilcox; RC - Research-Cottrell

Spray Drying Principle

Spray drying is the transformation of a pumpable fluid feed (solution slurry) into a particulate dried product, in a single drying process. It has to be assumed that the basic principle of spray drying is well documented, although, the method of operation of the spray dryer absorber is relatively simple. The sorbent solution of the slurry is atomized into the incoming flue gas stream to increase the liquid/gas interface and to promote mass transfer of the SO_2 from the gas to the slurry droplets, where it is absorbed. Simultaneously, the energy of the gas evaporates the water in the droplets to produce a dry powder mixture of sulfite/sulfate and some unreacted alkali. Gas then passes through the second stage fabric filter where the dry product is collected and a percentage of the unreacted alkali reacts with the SO_2 for further removal.(2)

Chemical Reaction/Temperature

A great similarity to pure coal-fired boiler/fly ash applications can't be denied; however, the most significant difference between fly ash collection and conditions in twin technology applications is continuous operation temperature.

The chemical interactions - when lime particles and SO_2 in the flue gas form sulfite, respective sulfate - takes place most economically closest to the moisture dewpoint - in the wet phase - thus representing an operation temperature range between 130°F to 160°F in the spray dryer absorber. It is the upset conditions - the fact that the lime/water injection is "off-line" - when suddenly the baghouse inlet temperature may raise to heat exchanger outlet conditions between 340°F to 380°F and the temperature requirement for the filter bag fabric has to accommodate these conditions. Practically only glass - woven, or needled fabrics - can withstand these requirements, provided that more expensive fabrics like Teflon^R or PBI^R or others would not be considered viable candidates.

Bypass or dilution would basically solve any sudden temperature surge in the baghouse. It is then obvious that the more attractive homopolymer acrylic fabrics - woven or needled - not only would cost less to install, but promises to be used at higher air-to-cloth ratios than glass. The decision, however, as to which system should get preference is site specific and can probably not generally be addressed. It also depends sometimes on regulatory aspects, which may differ from state to state.

Combustion Efficiency

Combustion efficiency has not been necessarily a major factor in the design stage of a number of existing units. As it has turned out, at least in one installation, the coal quality and the amount of unburned carbon had different effects on baghouse performance. A larger amount of unburned carbon would allow very fine particles to reach the filter bag surface. Naturally, this can contribute to blinding. If, in addition, moisture - in the liquid phase - is present, this problem multiplies itself and should either be operationally resolved or considered in a more conservative design ratio. The inlet loading expected, for instance, at 1 - 2 gr/cu.ft. may increase to as much as 15 gr/cu.ft. hence, creating a much thicker dust layer on the fabric. This requires either a more frequent cleaning or cleaning at higher pressure, in long term, however, affecting filter bag life especially with the more fragile glass fabrics.

Boiler Load

Boiler load may vary particularly in an industrial application, so it is recommended that air-to-cloth ratios are based on maximum load rather than on average load, since it is very difficult to predict how frequent maximum load conditions may prevail. If sometimes in the winter season a boiler has to meet additional heating requirements, it is advisable to consider these factors at an early stage of design, since maximum load conditions may last several months of operation.

Temperature Control

Temperature control in SO_2 dry scrubbing systems is based on the amount of water being needed to cool the incoming gas to the desired "interface" condition. One is trying to operate these systems as close as practically possible to the dewpoint. One has to prevent condensation conditions, on the other hand, since excessive water will eventually blind the filter bags and also create problems with corrosion in the baghouse and ash handling system, notably in the hopper section. If, for instance, the spray dryer in the startup mode is fed with water only to balance the temperature prior to introducing lime slurry, a very small amount of SO_3 content in the flue gas raises the acid dewpoint significantly. This may have disasterous effects on the filter material as well as eventually on the metal surfaces like cages, walls, doors, etc. Such conditions should be avoided or at least reduced to a minimum.(Table 2)

In summary, the temperature range at which systems are operated obviously has the most profound effect on SO_2 removal efficiency and, therefore, maintaining this temperature range is vital to a fully economic and successful installation.

Fibers and Fabrics

Basically speaking, as of today only two fibers are generally considered for these systems. These are glass and homopolymer acrylic. Both fibers are available in fabrics made from woven yarns, respective from needled material.(3) Each of the four types are currently under full-scale tests:

1. Needled homopolymer acrylic at Strathmore with excellent results for more than 18 months.

2. Needled felt glass at Celanese with interesting, although conflicting, results with the first set of bags for about 10 months, but the second set working very well since November, 1980.

TABLE 2

	Fiber — Generic Name	Cotton	Wool	Polyamid	Polypropylene
	Fiber — Trade Name			Nylon 66	Herculon^R
	Recommended continuous operation temperature (dry heat)	180°F 82°C	200°F 94°C	200°F 94°C	200°F* 94°C
	Water vapor saturated condition (moist heat)	180°F 82°C	190°F 88°C	200°F 94°C	200°F 94°C
	Maximum (short time) operation temperature (dry heat)	200°F 94°C	230°F 110°C	250°F 121°C	225°F 107°C
	Specific density	1.50	1.31	1.14	0.9
	Relative moisture regain in % (at 68°F & 65% relative moisture)	8.5	15	4. - 4.5	0.1
	Supports combustion	Yes	No	Yes	Yes
	Biological resistance (bacteria, mildew)	No, if not treated	No, if not treated	No Effect	Excellent
AT OPERATING TEMPERATURES	Resistance to alkalies	Good	Poor	Good	Excellent
	Resistance to mineral acids	Poor	Good	Poor	Excellent
	Resistance to organic acids	Poor	Good	Poor	Excellent
	Resistance to oxidizing agents	Fair	Fair	Fair	Good
	Resistance to organic solvents	Very Good	Very Good	Very Good	Excellent
	Comments				*250°F for Type 154 (under development 8/80

TABLE 2

	Fiber — Generic Name	Polyester	Acrylic Copolymer	Homopolymer Acrylic
	Trade Name	Dacron^R	Orlon^R	Dralon T
	Recommended continuous operation temperature (dry heat)	270°F 132°C	248°F 120°C	284°F 140°C
	Water vapor saturated condition (moist heat)	200°F* 94°C	230°F 110°C	260°F 125°C
	Maximum (short time) operation temperature (dry heat)	300°F 150°C	248°F 120°C	284°F 140°C
	Specific density	1.38	1.16	1.17
	Relative moisture regain in % (at 68°F & 65% relative moisture)	0.4	1.0	1.0
	Supports combustion	Yes	No	Yes
	Biological resistance (bacteria, mildew)	No Effect	Very Good	Very Good
AT OPERATING TEMPERATURES	Resistance to alkalies	Fair	Fair	Fair
	Resistance to mineral acids	Fair +	Good	Very Good
	Resistance to organic acids	Fair	Good	Excellent
	Resistance to oxidizing agents	Good	Good	Good
	Resistance to organic solvents	Good	Very Good	Very Good
	Comments	*Not Recommended		

TABLE 2

	Fiber	Generic Name	Aramid	Glas	PTFE	Metal
		Trade Name	Nomex^{R}	Fiberglass^{R}	Teflon^{R}	Bekinox^{R}
	Recommended continuous operation temperature		400°F 204°C	500°F 260°C	500°F 260°C	840°F 450°C
	Water vapor saturated condition (moist heat)		350°F 177°C	500°F 260°C	500°F* 260°C	750°F 400°C
	Maximum (short time) operation temperature (dry heat)		450°F 232°C	550°F 290°C	550°F 290°C	950°F 510°C
	Specific density		1.38	2.54	2.3	7.9
	Relative moisture regain in % (at 68°F & 65% relative moisture)		4.5	0	0	0
	Supports combustion		No	No	No	No
	Biological resistance (bacteria, mildew)		No Effect	No Effect	No Effect	No Effect
AT OPERATING TEMPERATURES	Resistance to alkalies		Good	Fair	Excellent	Very Good
	Resistance to mineral acids		Fair	Very Good	Excellent	Very Good
	Resistance to organic acids		Fair +	Very Good	Excellent	Very Good
	Resistance to oxidizing agents		Poor	Excellent	Excellent	Very Good
	Resistance to organic solvents		Very Good	Very Good	Excellent	Very Good
	Comments				*475°F for reverse air & shaker collector	

3. Woven glass at Northern States Power in operation since early 1981.

4. Woven homopolymer acrylic fabric at Coyote in operation since early 1981.

Depending on the baghouse system (inside or outside collection) the fabric selection depends on the cleaning method.(4)

The cleaning method, on the other hand, depends on the type of baghouse, whereas Reverse Air and Shaker baghouses (the names originate from the cleaning action) require woven fabrics, whereas the pulse jet/cage type (outside collection system) calls for the more efficient needled fabrics. Needled felts are of a textile structure in which single fibers are mechanically interlocked. Normally, a scrim is sandwiched in the center of the felt between two fiber layers. The unique feature of needled felts is that the single fiber is the active element in removing submicron size particles. Sometimes special woven glass fabrics are being used on cage type collectors, but this represents, basically speaking, an exception.

Woven glass which is successfully used in large-scale coal-fired utility applications, allows temperatures up to 500°F and short surges up to 550°F. Chemically treated glass fabrics have a very good chemical resistancy, however, being used in Reverse Air systems, with air-to-cloth ratios mainly at 2:1, represents for many users a compromise. It is only when woven glass fabrics (special constructions) are being used on outside/cage type collectors with special design cages, off-line cleaning, and the other important precautions, that woven glass fabrics can be used at 4:1 and 4½:1 air-to-cloth ratios.

Needled Glass

Needled glass, today, domestically available from two sources, is so far successfully applied to outside cage type collectors. The use of these fabrics in SO_2 dry scrubbing systems is currently being tested. The temperature capability of these fabrics is approximately the same as for woven glass fabrics. The air-to-cloth ratio should be approached rather conservatively since experience has shown that high amounts of unburned carbon as well as moisture can lead to blinding and so the air-to-cloth ratio of 3½ to 4:1 seems appropriate for twin technology applications. Addressing air-to-cloth ratios like in fly ash applications, the kind of boiler (stoker vs. P.C.) has great influence on the design ratio.

Homopolymer Acrylic

Homopolymer acrylic is considered already in one large SO_2 dry scrubbing system, but is a viable fabric in many metal applications for many years. Woven homopolymer acrylic fabrics can be used in Reverse Air as well as Shaker baghouses and can provide approximately 50% higher air-to-cloth ratios as compared to woven glass on inside collecting systems (woolen system yarn fabrics). Homopolymer acrylic Dralon T is more economical than glass; the temperature limitation, however, is 284°F.

Homopolymer acrylic needled felts can be used at air-to-cloth ratios between 4 and 6:1 if the fabric is special manufactured and, most importantly, exhibits a special surface treatment. The difference between standard Dralon T needled felts and special manufactured, special surface treated Dralon T felts is significant, particularly looking at the application requirement in SO_2 dry scrubbing systems. The system very well may go through upset conditions, thus, could create a very moist environment in the baghouse. On the other hand, different load factors may provide significant differences in inlet loading conditions, at the same time, unburned carbon may accumulate much finer dust on the surface. It is for this reason that special surface treated felts should be chosen over somewhat less expensive regular felts, which simply do not hold up as well under such delicate working conditions.

These special treatments (HCE II, Permaguard^{TM}, Hi-Rel^{TM}, Swiftclean^{TM}, and Mirror Finish^{TM}, etc.) are available from different manufacturers.

Specific fabric specifications are available upon request, but not part of this paper.

Endnotes

1. "Spray Dryer FGD Capital and Operating Cost", M. Drabkin and E. Robinson, Houston, October 1980.

2. "Modeling The Spray Absorption Process For SO_2 Removal", Journal APCA, December 1979.

3. "Needled Felts for Fabric Filters", ENVIRONMENTAL SCIENCE AND TECHNOLOGY, December 1979, Lutz Bergmann, Filter Media Consulting, Inc.

4. "Fiber/Fabric Selection for SO_2 Dry Removal Baghouse Systems", POWER ENGINEERING, October 1980, Lutz Bergmann, Filter Media Consulting, Inc.

TWO-STAGE DRY FLUE GAS CLEANING USING CALCIUM ALKALIS

By: D. C. Gehri, D. F. Dustin, and S. J. Stachura
Energy Systems Group
Rockwell International
8900 De Soto Avenue
Canoga Park, California 91304

ABSTRACT

Most of the dry flue gas cleaning (FGC) systems that have been sold to date will utilize high-calcium lime as the alkali reactant for SO_2 removal. In a two-stage, dry FGC system, optimum performance and utilization of lime is achieved by the special technique of gas bypass around the first-stage spray dryer and/or by recycle of particulates removed in the second-stage collector.

This paper presents three examples of dry FGC system performance with lime using the special techniques mentioned above. Three types of coal are considered: (1) a low-sulfur western subbituminous, (2) a medium-sulfur lignite, and (3) a high-sulfur eastern bituminous. The required FGC systems are discussed in terms of the lime preparation equipment, the flue gas cleaning equipment, and waste disposal techniques.

An economic evaluation of the three dry FGC systems is given along with a comparison to equivalent electrostatic precipitator-wet scrubber combinations. As shown by the comparisons, a two-stage, dry FGC system can be economically employed for all the given fuel types.

INTRODUCTION

A two-stage, dry FGC system consists of a first-stage spray dryer, which functions as the primary SO_2 absorber, followed by a second-stage fabric filter, which functions as the particulate collector as well as providing another stage of SO_2 absorption. Of the many alkalis tested for potential use in the system, the current preference is high-calcium, pebble lime, slaked under optimum conditions to produce a reactive slurry containing $Ca(OH)_2$ particles of minimum size and maximum specific surface area.

Optimized performance in the spray dryer is achieved by operating at outlet temperatures as close as practical to the adiabatic saturation temperature, while still producing a dry, collectable product. After collection, a fraction of that product can be reslurried and recycled through the spray dryer to supplement the SO_2 absorption of the freshly slaked lime.

Reliable operation of the fabric filter typically requires inlet temperatures somewhat above the optimum spray dryer outlet temperature. This can be achieved by a partial bypass of flue gas around the spray dryer to provide the necessary reheat. When bypass is used, the SO_2 absorption capability of the fabric filter is a key element in overall system optimization.

SYSTEM APPLICATIONS

In order to illustrate the performance of two-stage, dry FGC systems, we have selected three examples of 500-MW utility boilers, each fired with a different type of fuel. The essential boiler, fuel, and flue gas characteristics for these applications are given in Table 1. These characteristics were derived from TVA study premises with two exceptions and one addition. The exceptions are:

1) It was assumed that all of the fuel sulfur converts to SO_2 in the flue gas and that the FGC system must meet NSPS requirements based on that assumption. The TVA premises account for some sulfur retention in the ash and reduce SO_2 removal requirements to reflect that retention. Our assumption clearly imposes a more stringent performance requirement on the FGC system and is consistent with the typical commercial specifications for performance guarantees.

2) The lignite example is for a fuel containing 1.5% sulfur (dry basis), whereas the TVA base case uses 0.9% sulfur. This higher sulfur level was chosen to reflect a typical maximum sulfur for North Dakota lignite and to provide an example of intermediate (~80%) SO_2 removal requirements.

The one addition to the TVA premises is in the category of active ash alkalinity. The numbers given in Table 1 reflect our experience in titrating the given types of fly ashes to ascertain their potential value for recycle. It should be noted that this parameter is indicative, but not necessarily definitive as a measure of fly ash SO_2 absorption capacity in a dry FGC system.

The Western Subbituminous Application

For the western subbituminous application, the FGC system has been optimized using warm gas bypass. This technique involves bypassing flue gas from downstream of the air heater to provide reheat before the fabric filter. As shown in Table 2, a 10% bypass of the 300°F flue gas provides 15°F of reheat. With a 17°F approach to the adiabatic saturation temperature (T_{AS}) at the dryer outlet and the 15°F of reheat, the 165°F fabric filter inlet temperature is 35°F above the water dew point (T_d). Note that T_d is typically 2 or 3°F less than T_{AS}. With the specified 50% recycle (defined as the fraction of total collected product that is recycled), the "apparent utilization" in the system is 100%. This measure of system performance is the amount of SO_2 removal compared to that which could be removed by reaction of the total available CaO in the fresh lime feed.

As shown in Table 2, the contribution of the fly ash alkalinity is significant. The difference between the actual lime utilization of 86.7% and the "apparent utilization" of 100% reflects that contribution. In general, the relative contribution of an active fly ash is greatest for the low-sulfur, low-removal applications in which recycle can be maximized without slurry pumping problems. In fact, "apparent utilizations well above 100% can often be achieved." In this particular example, a potential of 120% exists. However, the only reliable technique to establish the optimum recycle fraction is to test. Frequently, the incremental utilization improvements beyond a certain recycle fraction do not justify the costs involved.

TABLE 1. EXAMPLE APPLICATIONS - 500-MW BOILERS

Fuel Type	Western Subbituminous	North Dakota Lignite	Eastern Bituminous
Boiler Heat Rate (Btu/kWh)	10,500	11,000	9,500
Fuel Sulfur (%, dry basis)	0.7	1.5	3.5
Flue Gas Flow (acfm, @ 300°F)	2,030,000	2,160,000	1,690,000
SO_2 in Flue Gas* (lb/h)	6,150	15,800	27,300
Fly Ash in Flue Gas+ (lb/h)	32,000	48,000	49,000
Active Alkalinity§ in Fly Ash (lb/h of CaO)	1,000	2,000	500
Adiabatic Saturation Temperature (°F)	133	137	122
NSPS SO_2 Removal (%)	70	79.1	89.5

[*] Assumes all of sulfur in fuel converts to SO_2

[+] Assumes 80% of ash in fuel becomes fly ash

[§] Typical quantities for given fuel type based on mineral composition of fly ash.

The Lignite Application

Warm gas bypass has also been selected for the lignite application. In this case, the lowest recommended approach to T_{AS} of 15°F is used, and the 12% bypass fraction provides 18°F of reheat. The resulting 170°F fabric filter inlet temperature is again 35°F above T_d. With the specified 60% recycle fraction, the "apparent utilization" is 96%. This recycle fraction is about the maximum possible without reaching the slurry pumping limits. Fly ash alkalinity utilization of 59% has, therefore, been optimized.

Even though the SO_2 removal is greater, the actual lime utilization of 85.7% is close to that for the previous example. This is partially due to the closer approach to T_{AS} and partially due to the greater recycle fraction.

TABLE 2. SYSTEM PERFORMANCE SUMMARIES

Fuel Type	Western Subbituminous	North Dakota Lignite	Eastern Bituminous
FGC System Temperature Profile (°F)			
. Dryer Inlet	300	300	300
. Dryer Outlet	150	152	137
. Fabric Filter Inlet	165	170	155
. Bypass Gas	300	300	750
Bypass Fraction (%)	10	12	3
Recycle Fraction (%)	50	60	50
Pebble Lime* Used (lb/h)	4,200	12,700	28,200
SO_2 Removal (%)	70.2	79.4	89.6
Apparent Utilization (%)	100	96	84
Actual Lime Utilization (%)	86.7	85.7	83.3
Actual Active Fly Ash Utilization (%)	50	59	49
Product+ for Disposal (lb/h)	41,200	75,400	105,800

* Assumes 90% available CaO in the lime

+ Assumes average molecular weight of $CaSO_x$ product is 128.

The only possibility for further utilization improvement is in the selection and/or slaking of the pebble lime. All of the examples of this paper are based on the implicit assumptions that the lime used is at least of "medium reactivity" as defined by the AWWA slaking rate test (1), and that the slaking temperature is controlled at 185° ±15°F using ball mills or paste slakers. The use of a "high reactivity" lime and/or closer control of slaking temperature (i.e., 190 ±5°F) might provide some small improvement. As a practical matter, such improvement would have a limited impact on system economics.

The Eastern Bituminous Application

For this application, the FGC system has been optimized using hot gas bypass. This technique involves bypassing flue gas from upstream of the air heater and results in a minor penalty to the boiler heat rate. However, it is usually the choice when 90% or greater SO_2 removal is required. A 15°F approach to T_{AS} is again employed in the spray dryer, and the 3% hot gas bypass results in a fabric filter inlet temperature 35°F above T_d. The recycle fraction of 50% results in a slurry of maximum practical density, so the system has been optimized.

The important thing to note about this example is the relatively small contribution of the fly ash alkalinity. Recycle is primarily useful in providing a chance for the excess unreacted $Ca(OH)_2$ to aid in SO_2 removal. The importance of high-quality pebble lime and proper slaking techniques are obvious. The key concern, however, is not a few percentage points of utilization. Rather, it is the economics of a two-stage, dry FGC system using lime, versus a wet scrubber using limestone, for this application.

Waste Disposal

The product of a two-stage, dry FGC system is a dry mixture of fly ash, $CaSO_4$, $CaSO_3$, and unreacted lime. For all of the examples in this paper, the fraction of unreacted lime is less than 5 wt %. The fly ash/$CaSO_x$ ratio varies from 4:1 for the western subbituminous application to 1:1 for the eastern bituminous application. In its dry state, the waste material can be handled in the same manner and with the same equipment as pure fly ash. A simple landfill operation is a suitable disposal technique (2), although alternate disposal methods and/or end product uses are being explored. For purposes of economic comparisons, landfill will be the basic disposal method evaluated.

ECONOMICS

This paper will base its economic comparisons on a report prepared by TVA for EPA comparing a "generic" lime spray dryer FGD system with a wet limestone-electrostatic precipitator system for a low-sulfur, western subbituminous application (3). That report provides the "base case" data from which all other economics in the paper have been extrapolated. These extrapolation techniques were devised by the authors of this paper who take full responsibility for their validity. No endorsement by TVA or EPA is implied nor intended.

Capital Investment

The capital investment comparison of Table 3 are based on mid-1982 costs. For the dry FGC systems, the base system costs were taken directly from the EPA-TVA report (3). Extrapolation techniques used for the other cases are listed below:

1) Material Handling and Feed Preparation

    1.3 x base for lignite system
    1.5 x base for eastern system

2) Gas Handling - Directly proportional to total gas flow

3) SO_2 Absorption - Directly proportional to gas flow to spray dryers

4) Particulate Removal - Directly proportional to total system gas flow

5) Recycle

2 x base for lignite and eastern systems

6) Disposal - Directly proportional to quantity of waste.

TABLE 3. CAPITAL INVESTMENT* COMPARISONS - 500-MW SYSTEMS

System	Base TVA-Dry	Western Dry	Lignite Dry	Eastern Dry	Base TVA-Wet	Western Wet	Lignite Wet	Eastern Wet
Material Handling and Feed Prep.	3.04	3.0	3.0	4.5	1.99	2.0	2.6	3.0
Gas Handling	7.19	7.2	7.7	6.2	9.92	9.9	10.4	8.4
SO_2 Absorption	7.17	7.7	8.2	7.2	13.73	13.7	17.2	15.7
Particulate Removal	11.13	11.1	11.6	10.0	12.40	12.4	12.9	10.5
Recycle	1.43	1.4	2.8	2.8	0	0	0	0
Disposal	1.22	1.2	2.2	3.2	6.16	6.1	9.0	12.2
Other (including indirects)	34.99	35.4	40.6	38.1	48.91	48.9	57.9	55.2
Totals	66.17	67	77	72	93.11	93	110	105

* All costs shown in millions of dollars.

For the wet FGD systems (including an ESP), the base system costs were again taken from the referenced report. Extrapolation techniques for all cost categories were the same as used for dry FGC systems, except that disposal system costs are not proportional to waste quantity, but rather 1.5 x base for lignite and 2 x base for eastern. This is significantly lower than an extrapolation based on waste quantity.

The two-stage, dry FGC systems are much lower in capital cost than wet scrubber-ESP combinations for all of the example applications. It is interesting to note that the 500-MW lignite-fired boiler requires a more expensive wet or dry system than its high-sulfur eastern counterpart.

Revenue Requirements

The revenue requirement comparisons of Table 4 are based on 1984 costs and include a $75/ton cost for lime and an $8.50/ton cost for limestone. The levelizing factor used in all costs, except capital charge, was 1.886. The capital charge is a levelized cost of 14.7% of the total investment.

TABLE 4. REVENUE REQUIREMENT* COMPARISONS - 500-MW SYSTEMS

System	Base TVA-Dry	Western Dry	Lignite Dry	Eastern Dry	Base TVA-Wet	Western Wet	Lignite Wet	Eastern Wet
Raw Materials	1.03	0.9	2.6	5.8	0.13	0.2	0.6	1.2
Labor and Supervision	0.95	1.0	1.2	1.4	1.32	1.3	1.5	1.7
Electricity	1.48	1.5	1.6	1.3	1.76	1.8	1.9	1.6
Maintenance	1.94	2.0	2.2	2.0	3.47	3.5	4.2	4.0
Capital Charge	9.73	9.8	11.3	10.6	13.70	13.7	16.2	15.4
Other	1.91	1.9	1.9	1.9	3.12	3.1	3.1	3.1
First Year Annual	17.04	17.1	20.8	23.0	23.50	23.6	27.5	27.0
Levelized Annual	23.52	23.6	29.2	34.0	32.19	32.4	37.5	37.3

* All costs shown in millions of dollars.

Extrapolation techniques used are as follows:

1) Raw Materials - See Table 2 for lime quantites and assume 4, 12, and 25 tons/h or limestone for the three wet scrubber cases.

2) Labor and Supervision - Add \$200,000 to base for lignite and \$400,000 to base for eastern.

3) Electricity - Proportional to total gas flow.

4) Maintenance - Proportional to direct capital investment.

5) Other - No change from base.

As with the capital investments, the revenue requirements for the two-stage, dry FGC systems are all lower than those for the corresponding wet scrubber-ESP combinations. However, within the probable comparative accuracy of the original base case estimates ($\pm 10\%$) and the additional uncertainties caused by extrapolation, the first year annual and the levelized annual revenue requirements for the two eastern, high-sulfur systems could be about equal.

The obvious reason is the cost penalty of $\$4.6 \times 10^6$ for the use of lime, which on a levelized basis is $\$8.7 \times 10^6$ per year.

Conclusions

Two-stage, dry FGC systems have lower capital investments than comparable wet scrubber-ESP systems for all cases evaluated. They also have lower annual revenue requirements, except for the eastern, high-sulfur applications where the two alternatives could be about equal. On the basis of these comparisons, it is concluded that dry FGC systems can be economically employed on boilers burning coal with up to 3.5% sulfur.

ENDNOTES

References

1. A.W.W.A, "Standard for Quicklime and Hydrated Lime," Std B202-65.
2. Buschmann, J. C., et al., "Disposal of Wastes from Dry SO_2 Removal Processes," presented at Joint Power Generating Conference (September 1980).
3. EPA-TVA, "Preliminary Economic Analysis of a Lime Spray Dryer FGD System," EPA-600/7-80-050 (March 1980).

CONTROL OF SULFUR DIOXIDE, CHLORINE, AND TRACE ELEMENT EMISSIONS FROM COAL-FIRED BOILERS BY FABRIC FILTRATION

By: R. J. Demski, J. T. Yeh, and J. I. Joubert
Pittsburgh Energy Technology Center
U. S. Department of Energy
Pittsburgh, Pennsylvania 15236

ABSTRACT

Experimental programs carried out at the Pittsburgh Energy Technology Center (PETC) have demonstrated that fabric filtration systems are effective in controlling emissions of a number of pollutants resulting from the combustion of bituminous coal in boilers. In studies conducted in a 500 lb/hr coal-fired furnace equipped with a baghouse, it was found that the baghouse filter cake removed significant portions of the toxic trace elements mercury, selenium, arsenic, beryllium, lead, and cadmium. When operating the baghouse in combination with injection of dry sorbents such as nahcolite, trona, and sodium bicarbonate, approximately 95% removal of sulfur dioxide and chlorine was obtained.

In this paper, the previously reported study relating to control of trace elements is summarized. Emphasis is placed on the recently completed investigation of SO_2 control by dry sorbent injection. In the latter study, tests were conducted with coals ranging in sulfur content from 1 to 3 percent. Operating variables considered included baghouse temperature, baghouse cleaning cycle time, sorbent particle size, and the ratio of sorbent to sulfur. With the exception of baghouse cleaning cycle rate, each parameter had a significant effect on SO_2 removal.

INTRODUCTION

Until the latter half of the 1970's, the preferred method for particulate control in the utility industry was electrostatic precipitation. However, with increasing production of low-sulfur western coals, the utility industry is turning to baghouse filtration to deal with the high-resistivity fly ash produced when burning these coals (1-3). A recent study indicates that in meeting the new, more stringent EPA standards for particulate emissions (0.03 lb/million Btu), baghouses are significantly more attractive than ESP's for low-sulfur (<2 percent) coal, and are competitive with ESP's when high-sulfur (>3 percent) coal is burned (2).

Dry Flue Gas Desulfurization

In parallel with the increasing interest in baghouse filtration for particulate control, a considerable amount of development work has been conducted utilizing baghouses in conjunction with dry flue gas desulfurization systems (4-7). A dry FGD system is one in which an alkaline sorbent is injected into the boiler flue gas as a dry powder or aqueous slurry; the sorbent reacts with SO_2 to form a dry product containing sulfates and sulfites. The mixture of spent material and fly ash is separated from the gas stream by the baghouse, where additional reaction between the sorbent and SO_2 occurs. While ESP's can also be used in dry FGD systems, the use of baghouses has been favored.

Data reported in the literature indicate that sodium compounds are considerably more reactive than calcium compounds when injected into flue gas as dry powders, although reactivities of the calcium compounds (particularly lime) are increased when they are injected via a spray dryer system. The study described in this paper was confined to dry-powder injection tests with sodium bicarbonate, nahcolite (a sodium bicarbonate mineral), and trona (a sodium carbonate/bicarbonate mineral).

The objective of the tests conducted at PETC was to evaluate the relative effectiveness of the three $NaHCO_3$ sorbents mentioned in removing SO_2 from flue gas streams. The tests were carried out in an experimental furnace designed to burn 500 lb/hr of pulverized coal. Parametric studies were conducted to determine the effect of operating parameters on SO_2 removal efficiency and sorbent utilization (gram atoms Na converted to Na_2SO_4/gram atoms Na injected). Parameters varied were sorbent/sulfur ratio, sorbent particle size, and baghouse temperature and cleaning cycle time. Three types of bituminous coal were burned, ranging in sulfur content from 1 to 3.1 percent; the heating value of each coal was about 13,500 Btu/lb. All tests were conducted at an excess air level of 20 percent.

Control of Chlorine Emissions

The chlorine content of most American coals ranges from 0.01 to 0.5 percent. The chlorine content of Western coals is generally low, but higher levels are present in Central and Appalachian coals. Nearly all of the chlorine contained in coal is emitted to the atmosphere as hydrogen chloride when the coal is burned (8,9).

Chlorine emissions from large fossil-fuel burning installations are not currently regulated. However, because of the large quantities of coal burned in the United States, the quantity of hydrogen chloride emitted to the atmosphere is significant ($\approx$1.5 million tons/year). These emissions may contribute to acid rain formation as well as create an air pollution hazard in the vicinity of large power plants burning high-chlorine coal. Hence, while chlorine emissions are not currently regulated, the desirability of minimizing the emissions is obvious. In this paper, data are presented that indicate high levels of removal of chlorine from flue gases can be achieved in conjunction with dry sorbent flue gas desulfurization.

Control of Trace Element Emissions

Although toxic elements are present in very small quantities in coal, emissions of these elements to the atmosphere are not insignificant. Using the average values for trace element levels in 101 coals analyzed by the Illinois State Geological Survey (10), the potential total tonnages of trace elements released to the atmosphere are

Element	Amount in Coal, PPM	Amount Emitted, Tons/Year
Lead	34.8	24,673
Arsenic	14.02	9,940
Cadmium	2.52	1,787
Selenium	2.08	1,475
Beryllium	1.3	922
Mercury	0.2	142

A study was conducted in the PETC 500 lb/hr combustion test facility to determine to what extent each of these trace elements is retained in the fly ash captured in a baghouse filter (11). The effects of baghouse temperature, fly ash loading on the filter bags, and carbon content in the fly ash were investigated. Fly ash loading was controlled by baghouse pulse cycle, and the carbon content was controlled by varying the amount of excess air fed to the furnace.

EXPERIMENTAL

Combustion Test Facility

The 500 lb/hr combustion test facility is shown schematically in Figure 1. The furnace was designed to simulate the performance of an industrial steam generator. The unit is 7 feet wide, 5 feet deep, and 12 feet high, and has a volumetric heat liberation rate of about 16,000 Btu/hr-ft^3 at a thermal input of 6.5 million Btu/hr. The furnace walls are refractory-lined and water-cooled.

Coal is charged to the hopper, pulverized to a size consist of 70% minus 200 mesh, and then is conveyed by the primary air into a recycle coal loop where intimate mixing of coal and air occurs. Four adjustable exit tubes are connected to the recycle loop; these convey the primary air-coal mixture to each of the four burners. Secondary air at 600°F is fed through adjustable swirl vanes surrounding each burner. The flue gas exits the furnace at about 2000°F, passes through a convective heat transfer section, and is then used to preheat the secondary air to the desired inlet temperature. By controlling the air flow through the recuperative air preheater, the flue gas exit temperature can be maintained in the range of 300°-475°F.

The baghouse is a Mikro-Pulsaire* model manufactured by the Pulverizing Machinery Division of the Slick Corporation, and is 6 feet, 6 inches in diameter and 9 feet, 10 inches high. It contains 57 Nomex bags, 8 feet long x 4.5 inches OD. The unit is normally operated at air/cloth ratios of 4-4.5 feet/minute.

Dry Flue Gas Desulfurization Tests

The dry-sorbent injection system is shown schematically in Figure 2. This rather simple system provides reliable and accurate feeding of solid sorbent.

In most of the tests, dry sorbent was injected into the 12-inch diameter flue-gas duct at the exit of the preheater, 26 feet upstream of the baghouse. The nominal flue gas velocity in the duct is about 50 feet/second, which results in a gas/solid contact time of about 0.5 second prior to entering the baghouse. A few tests were conducted while injecting sorbent at the inlet of the baghouse.

Gas analyses, as well as temperatures, pressures, and flows, are recorded with a computerized data collection system. The flue gas is analyzed at four locations (see Figure 1): at the furnace outlet; at the air preheater outlet (prior to sorbent injection); at the baghouse inlet; and at the baghouse outlet.

Typical analyses of the nahcolite and trona used in the dry sorbent tests are given in Table 1. The nahcolite was supplied by Superior Oil Company from a mine near Rifle, Colorado. The trona was obtained from a Stauffer Chemical Company mine in Rock Springs, Wyoming. The sodium bicarbonate used was USP grade and was $\approx$ 100 percent $NaHCO_3$. Much of the parametric testing was conducted with this material because it is well characterized chemically and is available in carefully graded size consists with the following industrial designations: No. 3 (32 micron mean particle diameter); No. 1 (69 micron); No. 2 (110 micron); No. 4 (115 micron); and No. 5 (180 micron).

TABLE 1. TYPICAL ANALYSES OF NAHCOLITE AND TRONA

	Nahcolite	(Weight Percent)	Trona
$CO_3^{=}$	Not Detected		24.3
HCO_3^{-}	62.7		25.3
Na	22.1		24.9
K	0.1		0.2
Ca	0.65		1.3
Mg	0.5		0.6
	86.05		76.6

---

*Reference herein to any specific commercial product, process, or service is to facilitate understanding and does not necessarily imply its endorsement or favoring by the United States Department of Energy.

Most of the tests were conducted with a 1.6-percent-sulfur Pittsburgh seam coal. Twelve tests were carried out with a 3.1-percent-sulfur West Virginia coal, and two tests with a 1.0-percent-sulfur Kentucky coal.

Chlorine Removal Tests

The chlorine removal study was conducted during two dry-sorbent injection tests with nahcolite and one test with sodium bicarbonate. Pittsburgh seam coal, containing 0.11 percent chlorine, was burned in each test, and the baghouse temperature was maintained at 400°F.

Gas samples were extracted from the stack (after the baghouse) through a glass probe and tubing. Approximately 100 ft^3 of gas was drawn through a fritted-disc bubbler immersed in an ice bath; this was followed by a dry ice/acetone bath to condense residual moisture. The Volhard technique was used to determine the amount of chlorine in solution.

Trace Element Removal Tests

The trace element removal tests were conducted while burning Pittsburgh seam coal containing the following levels of trace elements:

Element	Amount, PPM
Arsenic	8.3
Lead	7.9
Beryllium	1.38
Selenium	1.25
Mercury	0.15
Cadmium	0.14

The baghouse was operated at temperatures ranging from 275° to 365°F. The fly ash loading on the filter bags was varied over the range of 0.0003 to 0.05 lb/ft^2 by adjusting the baghouse cleaning cycle rate, and the carbon content of the fly ash was controlled at values ranging from 5 to 20 percent by varying the excess air level. Details of the analytical procedures used in this study were reported previously (11).

RESULTS AND DISCUSSION

Dry Flue Gas Desulfurization Tests

Results of the dry flue gas desulfurization tests are summarized here. A more detailed report of this investigation will be published in the near future (12).

Sodium Bicarbonate Tests

Most of the parametric and exploratory testing was carried out with USP sodium bicarbonate. In general, tests with the other sorbents were confined to varying the Na_2/S ratio at a fixed set of operating conditions.

The effect of baghouse temperature was examined over the range of 350°-450°F. Number 1 (69 micron) sodium bicarbonate was used at a Na_2/S ratio of 1.3. The SO_2 removal efficiency was found to level off at temperatures in excess of 400°F. With the other sorbents, a temperature of 400° also appeared near optimal in terms of SO_2 removal, and this temperature level does not represent a severe operating condition for the baghouse. Thus, most of the testing was carried out at approximately 400°F.

To determine the effect of sorbent particle size on SO_2 removal, a series of tests was conducted with sodium bicarbonate at a Na_2/S ratio of 2 and a baghouse temperature of 400°F. The SO_2 removal efficiency varied approximately linearly with the mean particle diameter of the sorbent. The data indicated that SO_2 removals of 90 percent are achievable at mean sorbent diameters of 65 microns or less. For a stoichiometric ratio of 2, this corresponds to a sorbent utilization of 45 percent. However, in a series of tests with No. 3 sodium bicarbonate (32 micron diameter), it was found that 90 percent SO_2 removal could be attained at a Na_2/S ratio of 1.3, corresponding to about 70 percent sorbent utilization.

Tests with Nahcolite

A series of tests was conducted with Pittsburgh seam coal while injecting nahcolite with a mean particle diameter of 37 microns. Figure 3 shows the effect of Na_2/S ratio on SO_2 removal at 400° and 420°F. As expected from the earlier sodium bicarbonate tests, the slight difference in temperature appears to have no major effect on the removal achieved.

It should be noted that varying the baghouse cycle rate over the range 6 to 30 minutes also had no apparent effect on SO_2 removal. This was found to be true in all other tests performed, regardless of the sorbent employed. It is believed that this is an indication that reactions are confined to only a thin outer layer of sorbent deposited on the filter bags.

For the conditions stated in Figure 3, 90 percent SO_2 removal is achieved at a Na_2/S ratio of 1.1. This corresponds to 82 percent sorbent utilization.

Two tests were conducted with the Kentucky coal containing 1.0 percent sulfur, and six tests were conducted with the West Virginia coal containing 3.1 percent sulfur. Baghouse temperature was maintained at 400°-420°F, and the cycle times were either 15 or 30 minutes.

The results for the Kentucky coal, at Na_2/S ratios of 1.1 and 1.2, were consistent with the results obtained with the Pittsburgh seam coal indicated in Figure 3. However, the SO_2 removal efficiencies achieved when burning the 3.1%-S West Virginia coal were somewhat lower than those obtained with the Pittsburgh seam coal; a Na_2/S ratio of 1.5 was required to achieve 90 percent SO_2 removal. The reason for this is not apparent. Intuitively, one would anticipate greater reactivity with the West Virginia coal, as initial SO_2 concentrations should be higher than when burning Pittsburgh seam coal. The same phenomenon has been noted by others (13).

Tests with Trona

A series of ten tests was conducted with trona with a mean particle diameter of 59 microns while burning 1.6%-S Pittsburgh seam coal. Another series of seven tests was carried out with a second batch of trona (32 microns) while burning 3.1%-S West Virginia coal. The results are plotted in Figure 4. As in the case with nahcolite, higher SO_2 removal efficiencies were achieved while burning Pittsburgh seam coal than with West Virginia coal, although here the difference is more pronounced. In fact, if one were to adjust the West Virginia coal curve to account for particle size effects, the difference would be even greater (a decrease in SO_2 removal efficiency by approximately 3 percentage points at each Na_2/S ratio).

Chlorine Removal Tests

Results of the chlorine removal tests, carried out in conjunction with three dry FGD tests, are given in Table 2. All tests were conducted at a baghouse temperature of 400°F. In one of the tests, the sorbent Na_2/S ratio was varied over the range of 0.84-1.12, while in the other two tests, the Na_2/S ratios were maintained at 0.99 and 1.04, respectively.

Chlorine removal efficiencies ranged from 95.6 to 98.8 percent. These results indicate that even without attempting to optimize operating parameters, dry, Na-containing sorbents are extremely effective in reducing emissions of chlorine from coal-fired boilers.

TABLE 2. REMOVAL OF CHLORINE IN BAGHOUSE WHILE BURNING PITTSBURGH SEAM COAL CONTAINING 0.11 PERCENT CHLORINE; BAGHOUSE TEMPERATURE: 400°F

Sorbent	Nahcolite	Nahcolite	Sodium Bicarbonate
Mean Particle Diameter, μm	37	37	69
Na_2/S Ratio	0.84-1.12	0.99	1.04
Chlorine Fed with Coal, lb/hr	0.55	0.55	0.54
Chlorine in Flue Gas (after baghouse), lb/hr	0.024	0.0066	0.011
Chlorine Removal, Percent	95.6	98.8	98.0

Removal of Trace Elements

The amounts of the trace elements mercury, selenium, arsenic, beryllium, lead, and cadmium retained by baghouse fly ash and furnace bottom ash are given in Table 3. (These tests were conducted without sorbent injection.)

The contribution of the bottom ash is small, since only 10 percent or less of the coal ash remains in the furnace during a given test.

The retention of mercury and selenium was sensitive to baghouse loading. Loadings of 0.03 to 0.04 lb/ft^2 were required to achieve high levels of retention; these loadings correspond to baghouse cycle times of 35 and 60 minutes. Baghouse loading had no effect on retention of the other trace elements.

Baghouse temperature also affected the retention of mercury and selenium. Lower temperatures (270°-300°F) produced higher levels of retention.

The retention of mercury also appeared to increase with increasing carbon content of the fly ash. It is believed that this may be due to adsorption of mercury by the carbon.

Comparing these results to results reported by others (14,15), it is apparent that significantly higher retention of mercury, selenium, arsenic, and beryllium is possible with a baghouse than with an electrostatic precipitator. However, the levels of retention of lead and cadmium reported here are lower than values reported in other studies involving power plants equipped with ESP's. Material balances on these two elements indicated a significant fraction (25-60 percent) of each was unaccounted for in each test. Hence, the elements or their combustion products may have condensed out of the gas phase in cooler sections of the boiler upstream of the baghouse.

TABLE 3. TRACE ELEMENT RETENTION BY FLY ASH AND BOTTOM ASH

Element	Average Retention, Percent	Range, Percent
Mercury	100±18*	-
Selenium	100±13*	-
Arsenic	91	74-120
Beryllium	77	62-94
Lead	63	53-77
Cadmium	55	52-65

*Optimum Conditions

CONCLUSIONS

The FGD study discussed in this paper has confirmed that high levels of SO_2 removal can be achieved via dry powder injection of $NaHCO_3$-bearing sorbents into the flue gas of coal-fired boilers. The mineral nahcolite is particularly effective. Commercially produced sodium bicarbonate is slightly less reactive than nahcolite. The mineral trona was found to be less effective, probably due to the lower bicarbonate content of this material. With all three sorbents, SO_2 removal efficiencies in excess of 90 percent could be achieved, although in some cases at fairly low sorbent utilization efficiencies. Future investigations at PETC will focus on improving sorbent utilization while burning high-sulfur coals. A spray dryer system has been added to the test facility, and a sorbent recycle system will be installed. The planned work will include an evaluation of the effectiveness of lime and limestone slurry injection.

In tests conducted concurrently with the dry FGD tests, it was found that greater than 95 percent removal of chlorine was obtained with nahcolite and sodium bicarbonate. While emissions of chlorine from power plants are not currently regulated, this nevertheless represents a valuable additional benefit of dry FGD technology.

The emissions of the trace elements mercury, selenium, and arsenic can be effectively controlled via fabric filtration. Significant amounts of the elements beryllium, lead, and cadmium are also retained in the baghouse fly ash. The best results were obtained at baghouse temperatures lower than that required ($\approx$400°F) for SO_2 emission control by dry sorbent injection. However, when injecting sorbents as slurries using a spray dryer system, high SO_2 removal efficiencies can be achieved at flue gas temperatures significantly lower than 400°F. It appears probable, therefore, that boilers equipped with spray dryer/baghouse systems can be operated with minimal emissions of not only SO_2 and Cl_2, but also the major toxic trace elements.

REFERENCES

1. Reigel, S. A. and R. P. Bundy. Why the Swing to Baghouses? Power. January 1977. p. 68.
2. Anon. Chemical Engineering. December 31, 1979. p. 19.
3. Pruce, L. M. Interest in Baghouses on Upswing. Power. February 1980. p. 86.
4. Midkiff, L. A. Spray-Dryer System Scrubs SO_2. Power, 123, No. 1, 29, 1979.
5. Lutz, S. J., R. C. Christman, B. C. McCoy, S. W. Mulligan, and K. M. Slimak. Evaluation of Dry Sorbents and Fabric Filtration for FGD. Prepared by TRW, Inc. for U. S. EPA, EPA-600/7-79-005, January 1979.
6. Blythe, G. M., J. C. Dickerman, and M. E. Kelly. Survey of Dry SO_2 Control Systems. Prepared by Radian Corp. for U. S. EPA, EPA-600/7-80-030, February 1980.
7. Burnett, T. A., K. D. Anderson, and R. L. Torstrick. Spray Dryer FGD: Technical and Economic Assessment. Symposium on Flue Gas Desulfurization, Houston, Texas, October 28-31, 1980.
8. Kear, R. W. and H. M. Menzies. Chlorine in Coal: Its Occurrence and Behaviour during Combustion and Carbonisation. BCURA Monthly Bulletin, Vol. XX, No. 2, p. 53, February 1956.

9. Iapalucci, T. L., R. J. Demski, and D. Bienstock. Chlorine in Coal Combustion. U. S. Bureau of Mines, RI 7260, 1969.

10. Ruch, R. R., H. J. Fluskoter, and N. F. Shimp. Occurrence and Distribution of Potentially Volatile Trace Elements in Coal. Report, Illinois State Geological Survey, August 1974.

11. Yeh, J. T., C. R. McCann, J. J. Demeter, and D. Bienstock. Removal of Toxic Trace Elements from Coal Combustion Effluent Gas. U. S. Energy Research and Development Administration, PERC/RI-76/5, September 1976.

12. Yeh, J. T., R. J. Demski, and J. I. Joubert. Control of SO_2 Emissions by Dry Sorbent Injection. To be presented at the ACS Symposium on Advances in Flue Gas Desulfurization, Atlanta, Georgia, March 29-April 3, 1981.

13. Parsons, E. L., L. F. Hemenway, O. T. Kragh, T. G. Brna, and R. L. Ostop. SO_2 Removal by Dry FGD. Presented at the Symposium on Flue Gas Desulfurization, Houston, Texas, October 28-31, 1980.

14. Bolton, N. E., J. A. Carter, J. F. Emergy, C. Feldman, W. Fulkerson, L. O. Hulett, and W. E. Lyon. Trace Element Mass Balance Around a Coal-Fired Steam Plant. Fuel Chem. Preprints, 18(4):114-123, 1973. (ACS 166th National Meeting, Chicago, Illinois.)

15. Klein, D. H., et al. Pathways of Thirty-Seven Trace Elements Through Coal-Fired Power Plant. Environmental Science and Technology. October 1975. p. 973.

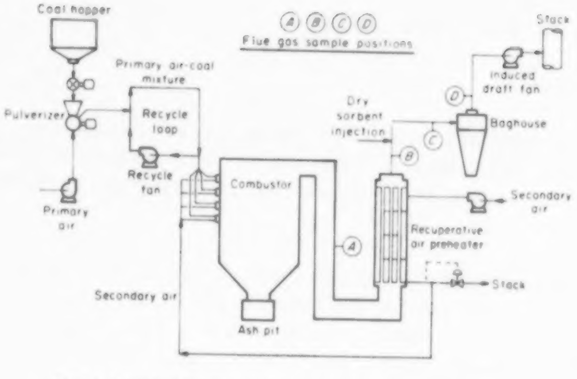

Coal hopper
A B C D
Flue gas sample positions
Stack
Primary air-coal mixture
Induced draft fan
Pulverizer
Recycle loop
D
Dry sorbent injection
Baghouse
C
B
Recycle fan
Combustor
Secondary air
Primary air
A
Recuperative air preheater
Stack
Secondary air
Ash pit

Figure I. Simplified flowsheet of 500lb/hr pulverized-coal-fired furnace

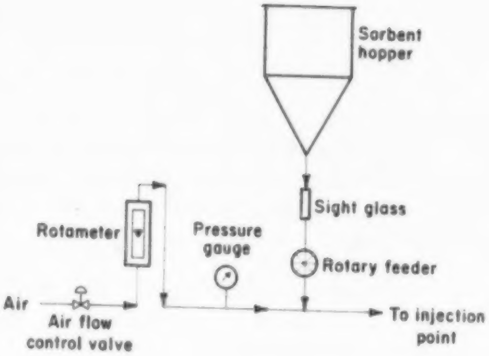

Sorbent hopper
Sight glass
Rotameter
Pressure gauge
Rotary feeder
Air
Air flow control valve
To injection point

Figure 2. Dry sorbent injection system

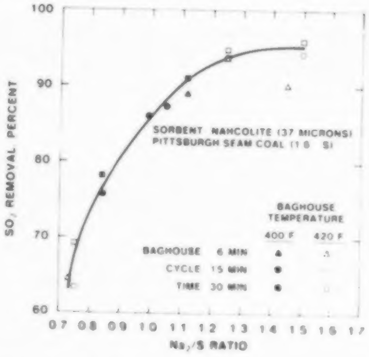


FIGURE 3. SO_2 REMOVAL WITH NAHCOLITE WHILE BURNING PITTSBURGH SEAM COAL

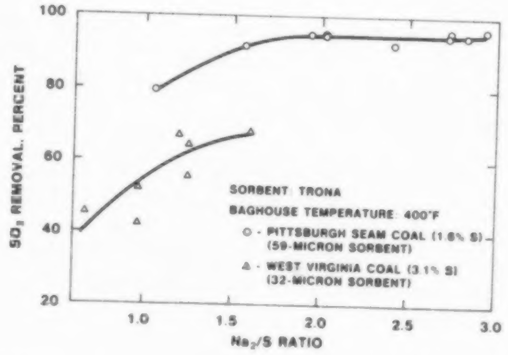


FIGURE 4. SO_2 REMOVAL WITH TRONA WHILE BURNING PITTSBURGH SEAM AND WEST VIRGINIA COAL

FLYASH COLLECTION USING A VENTURI SCRUBBER
MINNESOTA POWER'S COMMERCIAL OPERATING EXPERIENCE

By: Carlton A. Johnson
Peabody Process Systems, Inc.
835 Hope Street
Stamford, Connecticut 06907

ABSTRACT

Minnesota Power elected to use a venturi scrubber as a particulate removal device for Clay Boswell Station, Unit No. 4 (500 MW). The selection was based upon significant cost savings when compared to conventional precipitator technology.

Prior to start up of the full scale system, extensive pilot plant test work was conducted to determine performance characteristics related to both particulate removal and opacity. Unit No. 4, now in commercial operation, provides comparison of predicted performance based on pilot plant data with full scale system performance. This paper discusses the comparison of actual performance versus predicted performance.

INTRODUCTION

In December 1976 Minnesota Power awarded a contract to Peabody Process Systems for an Air Quality Control System for the 500 MW Clay Boswell Unit No. 4, Cohasset, Minnesota. The system was designed for integral particulate and SO_2 removal using a venturi and spray tower absorber. Selection of a venturi for particulate removal gave a 25 million dollar capital cost savings compared to using conventional electrostatic precipitator.

The design of the Air Quality Control System was based upon burning a sub-bituminous coal from the "Big Sky" mine at Coalstrip, Montana, where the Rosebud and McKay seams vary in sulfur content from 0.4% to 2.8% with approximately 10% ash content.

Prior to start up of the full scale system, extensive pilot plant test work was conducted to determine performance characteristics relating to SO_2 removal, particulate removal and opacity. Clay Boswell Unit No. 4, 500 MW started commercial operation in March of 1980. The performance of Unit No. 4 the full scale system, has since been compared with the earlier pilot plant results.

System Description

The system design criteria for Clay Boswell Unit No. 4 are shown in Table 1. Raw flue gas containing SO_2 and particulate enters the air quality control system (AQCS) via a ductwork plenum. The ductwork plenum distributes the raw flue gas to any three or four gas cleaning trains. Under full load conditions three gas cleaning trains are operational. The fourth gas cleaning train is a spare. Each train includes a venturi and absorber and is designed to function independently.

Table 1

DESIGN BASIS

Unit Generating Capacity	500 MW
Coal Sulfur Content	2.8%
SO_2 Emission Standards	1.2 lbs. SO_2/mm BTU
Particulate Emission Standards	0.1 lbs./mm BTU
Flue Gas Volume	2,207,000 ACFM
Percent of Gas Scrubbed	95 to 100%
No. of Gas Cleaning Trains	3 Operating/one spare
No. of Venturi Recycle Pumps/Trains	1 Operating/one spare
No. of SO_2 Absorber Recycle Pumps/Trains	2 Operating/one spare
Flue Gas Inlet Grain Loading	11 gr./SCF
Particulate Removal Efficiency	99.7%
SO_2 Removal Efficiency	90%
Alkali	Lime/flyash
Waste Solids Disposal Methods	Ponding
Reheat Method	None or 800°F Bypass gas

The raw flue gas distributed by the ductwork plenum enters the gas cleaning trains at the top of the venturi in each operating train where first stage cleaning - removal of particulate is accomplished.

The venturi selected for particulate removal is based on the radial-flow design concept. The venturi design must contend with the problems of abrasion and solids build-up due to hot gas contacting the slurry used for particulate removal. To avoid solids build-up, the venturi is designed using a "dentist bowl" concept. The upper section of the venturi consists of a conical section in which slurry is introduced tangentially. The quality of slurry used is several times greater than the potential evaporative capacity of the hot flue gas.

The excess quantity of slurry insures that the conical section is completely wetted thus eliminating solids build-up. Raw flue gas enters the venturi through an insulated thimble section which introduces the gas below the slurry injection point, keeping the gas/slurry contact point below the wet-dry line and eliminating solid build-up.

Inherent in the design of a venturi are three distinct areas where abrasion can occur. The first is where the gas makes a 90 degree turn to flow through the cylindrical orifice. Abrasion in this area is avoided by having the gas impinge on a pan filled with slurry, which absorbs the impact of the gas. This pan is maintained full by the flow of slurry from the "dentist bowl" and supplemental slurry added via a bull nozzle. The slurry required for the "dentist bowl" and the bull nozzle is pumped from the recycle tank.

The slurry overflow from the pan and the raw gas are mixed intimately in the cylindrical orifice around the pan. It is at this point that particulate removal is achieved.

The second area where abrasion can occur is at the orifice which cannot be eliminated. However, the wear surface in the orifice area is fabricated from disposable sections easily replaced which simplifies maintenance.

The third area is the wall section in the main shell of the venturi. The gas and slurry mixture leaving the orifice has a high velocity which if allowed to impact on a surface, also could cause severe abrasion problems. This situation is avoided by maintaining a sufficient distance between the orifice area and the wall of the venturi. This allows the gas to expand and slow down sufficiently to be nonabrasive. As an added precaution, the wall is rubber lined to withstand any residual abrasive impact.

The flue gas and slurry mixture then flow into and through the base of the absorber into the recycle tank. The slurry mixture is then pumped to the spray headers in the absorber for removal of SO_2 from the gas.

The absorber is a high-velocity spray tower design. Each absorber consists of six spray banks through which a slurry containing flyash is sprayed countercurrent to the gas flow. The gas, as a result of being contacted with the slurry is cleaned of SO_2. Under design conditions only four spray banks, two per recycle pump, are used. The other two spray banks and one recycle pump are spares.

After leaving the absorber zone, entrained slurry in the flue gas is removed by means of a two stage mist elimination section. The first stage is a weeping sieve tray deluged with a mixture of reclaimed water and river water.

Final de-entrainment, particularly of gas entrained water, is accomplished in a second stage which is a chevron type mist eliminator.

The wet gas leaving the absorber flows to a ductwork plenum from which it is distributed to four I.D. fans and then discharged to the stack. The gas system downstream of the absorber is designed to run with or without reheat. When reheat is desired, a slip stream of $800^{\circ}F$ flue gas taken ahead of the air preheater is injected into the outlet duct of each absorber via spargers. The reheat gas which amounts to approximately 5% of the total flue gas stream is cleaned of particulate by means of a precipitator prior to injection into the scrubbed gas.

Each module has a recycle tank which collects the slurry draining from both the venturi and the absorber. One pump circulates slurry to the venturi and three pumps are installed for circulation of slurry to the absorber. Two absorber spray headers are dedicated to each recycle pump only two of which operate at design conditions.

Waste slurry overflows from the recycle tank to a waste slurry sump which also collects all drainage and water used for system flushing. The waste slurry is then transported from the sump to a pond in which the solids are allowed to settle. The water reclaimed from the slurry is recycled back to the AQCS system for reuse. The system operates on a totally closed loop water balance basis.

Fresh water is added to the system to make up for losses resulting from evaporation and water bound with the waste solids.

In the event a purchased alkali (lime) should be required, a lime slaking system has been incorporated in the system. The lime is prepared as a 20 wt. percent slurry and fed to a storage tank. A lime slurry recirculation system transports the lime slurry to the modules.

As a site convenience, the owner elected to dispose of flyash collected in baghouses from Units No. 1 and 2 with the waste solids from Unit No. 4. To accomplish this the dry flyash from Units No. 1 and 2 is prepared as a slurry and fed to the Unit No. 4 AQCS system waste solids disposal.

Pilot Plant Testing and Results

The contract between Minnesota Power and Peabody guarantees both the particulate and SO_2 removal efficiencies. To further Minnesota Power personnels' indoctrination of the operating characteristics of the system and confirm the guarantees, a pilot plant test program was originated. The test program extended over a eighteen month period, objectives of the program included the following:

1. Confirm the pressure drop in the venturi required to meet particulate and opacity emission standards.

2. Confirm the system SO_2 removal efficiency of 90%, when burning coals containing up to 2.8% sulfur.

3. Demonstrate that the system can operate on a closed-loop water balance.

4. Determine the alkali utilization of the flyash.

5. Evaluate alternative alkalis.

6. Define waste solids characteristics such as settling rates, percent moisture, and settled solids.

The pilot plant (Fig. 1) to achieve the above objectives was installed on Unit #3 at the Clay Boswell station. Unit #3 has the same boiler design and is burning the same coals which are to be burned in Unit #4. Thus, the results obtained from the pilot plant could be considered representative of the results to be expected for Unit #4.

The pilot plant system was identical in concept to a proposed full-scale unit, with some modifications based on practical economical considerations. The lime slaker system was not installed. An in-line electric reheater was used in lieu of the hot gas bypass system. A thickener and vacuum filter were used in lieu of a waste solids pond system.

The pilot plant data demonstrated that the venturi performance is significantly affected by particle size distribution, as evidenced by particulate removal curve. (Fig. 2)

For particle sizes of 2.5 microns or larger, the percent removed is essentially 100%, regardless of venturi pressure drop. The percent removed drops off slightly as particle size decreases from 2.5 microns to 0.8 microns. It is in the less than 0.8 micron size range that the venturi pressure drop has the greatest significance.

Data was also plotted (Fig. 3 & Fig. 3A) showing the total outlet grain loading as a function of venturi pressure drop. The curves for both coals are shown. The venturi system had been based upon achieving a 0.03 gr./SCFD (0.06 lbs./MM BTU) using a 12 inch w.c. pressure drop. The curves show that with Rosebud coal the 0.03 gr./SCFD could be achieved with a 6 inch w.c. drop pressure, whereas the McKay coal required an 8 inch w.c. pressure drop. Both curves appear to indicate that regardless of pressure drop, outlet grain loadings significantly less than 0.01 gr./SCFD (0.02 lbs./MM BTU) are not achievable. Particulate removal performance was guaranteed by Peabody at a venturi pressure drop of 12 inch w.c.. The test data confirmed that this value could easily meet the required emission standards.

Opacity is a different problem. Test results showed that even with particulate loading significantly less than that required to meet emission standards a 20% opacity was not achievable. This is partially attributed to the fact that stack geometry is an important factor in estimating the measured opacity. The larger the stack diameter, the more difficult it becomes to achieve a low opacity value.

A significant cost benefit was also established for integral particulate and SO_2 removal. During the SO_2 removal study phase of the test program it was established that SO_2 emission standards could be met without the need for purchased alkali. The alkali in the ash is sufficient to satisfy SO_2 removal requirements. This cost benefit had not been included in the economic evaluation of the system.

Commercial Operating Results

Clay Boswell Unit No. 4 was started up in March 1980. During the start-up period the site was experiencing a strike of its operating and maintenance personnel. Consequently this was started up with a skeleton crew consisting of Minnesota Power supervisory personnel. Despite the lack of operation and maintenance resources the Air Quality Control System started up with only minor problems. The system entered formal commercial operation in May 1980.

At Design Sulfur Coal Conditions (2.8%) to comply with the 1.2 lbs., SO_2 MM BTU emission standard, a 90% SO_2 removal is necessary. However, at less than design sulfur coals environmental permit requirements also dictate a minimum SO_2 removal of 60%. Based on the actual coals burned, (Fig. 4) the 60% SO_2 minimum removal is the controlling emission criteria. Operation of the AQCS is therefore geared to meeting the 60% SO_2 removal standard.

The AQCS has the flexibility to save pumping power by allowing the recycle pumps for the absorber to be turned on and off as required. Generally, when less than design sulfur coals are burned, the quantity of slurry recirculated in the AQCS can be reduced. Two absorber recycle pumps are required for the maximum design sulfur coals. Under actual sulfur coal conditions, only one of the pumps is used, resulting in an operating power saving.

Pilot plant operation indicated that the recycle slurry should be constituted with a low pH to maximize the extraction of the alkali from the fly-ash. To this end a pH value of 4 or less has been maintained. SINCE COMMERCIAL OPERATION OF THE SYSTEM THE SO_2 EMISSION STANDARD HAS BEEN MET WITHOUT THE NEED TO USE ANY PURCHASED ALKALI.

Performance tests have shown that the SO_2 and particulate emission standards have been met. However, as predicted, stack opacity is significantly greater than 20%. These results confirm the pilot plant test data.

The full load operating requirements for Unit No. 4 are set forth in Table 2 below:

Table 2

	DESIGN % S COAL	NORMAL % S COAL
No. of Gas Cleaning Trains	3	3
No. of Operating Venturi Recycle pumps/trains	1	1
No. of Operating Absorber Recycle pumps/trains	2	1
System Pressure Drop inches w.c.	20	18
Power Requirement Excluding Draft Loss KW	4416	2771
% Rated Capacity	0.88	0.55
Lime Requirement-lbs./hr.	32241	0

At present two operators per shift (4 shift basis) are required. Minnesota Power had originally budgeted a greater number of operators, however, during start-up it became evident that two men/shift were adequate.

Since start-up, the system has evidenced almost a 100% availability. Except for approximately nine (9) hours during which a problem with a programmable controller was encountered, the AQCS has not restricted the generating capability of Clay Boswell Unit #4. (Fig. 5)

Conclusion

Clay Boswell Unit #4 has demonstrated that a venturi integrated with an SO_2 absorber is an economical and reliable Air Quality Control System. However, the question can be raised "in light of tighter particulate standards is the system viable?" The answer to this question is "yes" and "no".

As emission standards are tightened the pressure drop required will increase. As determined in the pilot plant tests, the key to venturi performance is the amount of sub-micron particles in the raw flue gas. For some coals the quantity of sub-micron particles is relatively low so that a reasonable pressure drop is needed to meet the current standard of 0.03 lbs./MM BTU. For other coals, particularly western coals, the flyash contains a large portion of sub-micron particles. This requires a very large pressure drop (20 w.c. or greater) which imposes a very severe energy penalty on the system. However, a new technology has emerged which promises to offset that penalty.

The new technology has been developed by Peabody and is labeled "Heatron". It is a wet tubular electrostatic precipitator which replaces the mist eliminator in the upper section of the SO_2 absorber. This device can achieve extremely high particulate removal efficiency with a minimal energy consumption.

Thus, today, an Air Quality Control System equipped with a "Heatron" and venturi or a modified version thereof can meet emission control requirements and achieve significant cost savings when compared to conventional systems using a dry electrostatic precipitator or baghouse.

Figure 1

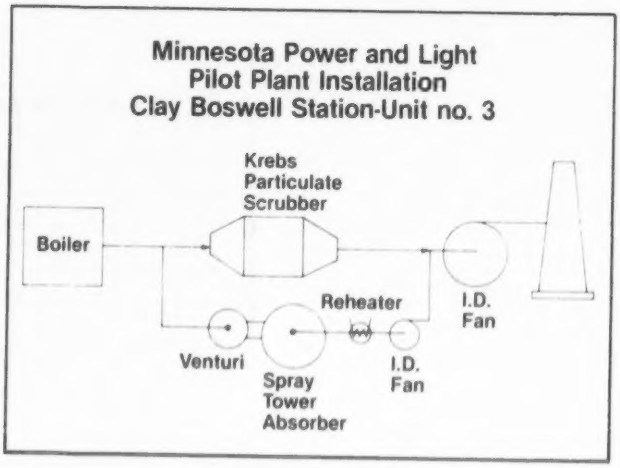

Minnesota Power and Light
Pilot Plant Installation
Clay Boswell Station-Unit no. 3
Krebs Particulate Scrubber
Boiler
Reheater
I.D. Fan
Venturi
Spray Tower Absorber
I.D. Fan

Figure 2

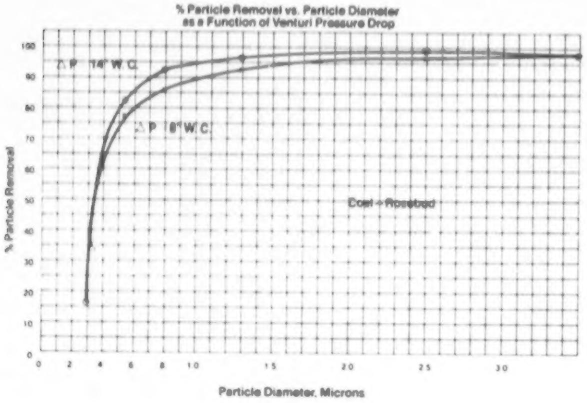


Figure 3

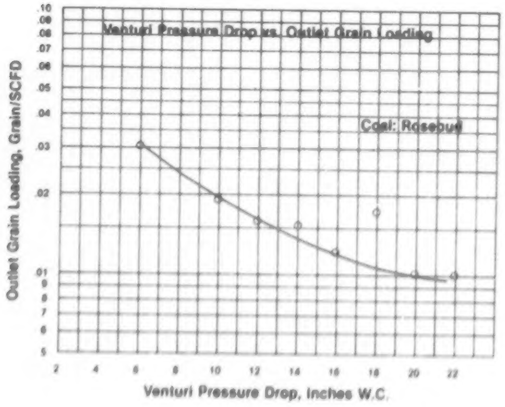


Figure 3A

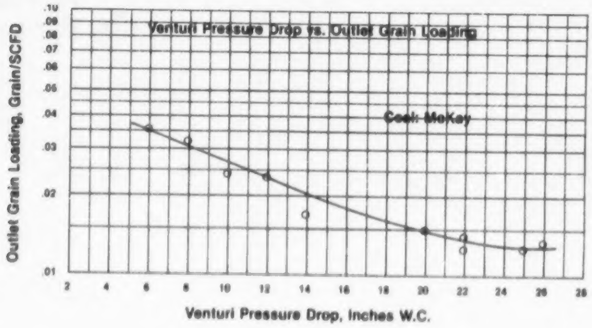


Figure 4

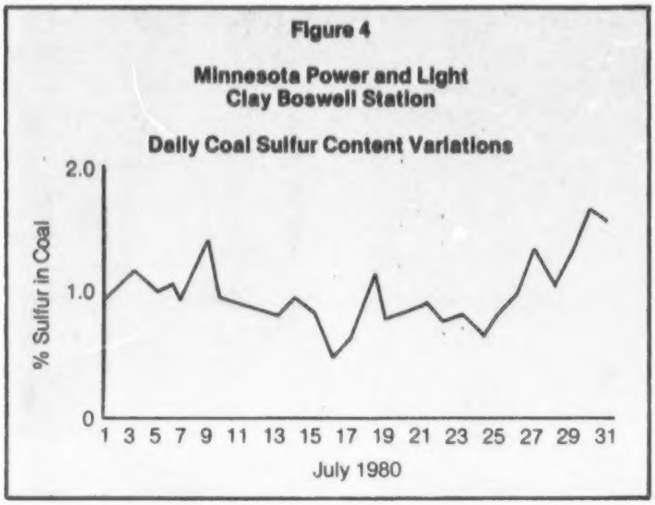


Figure 4

Minnesota Power and Light
Clay Boswell Station

Daily Coal Sulfur Content Variations

Figure 5

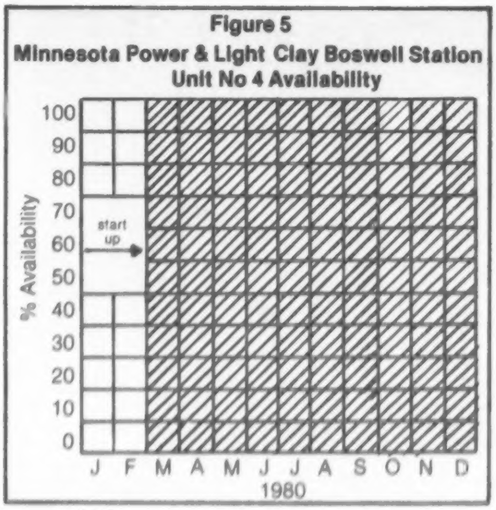


Figure 5

Minnesota Power & Light Clay Boswell Station
Unit No 4 Availability

AUTHOR INDEX

AUTHOR NAME	PAGE
Albrecht, P.R.	IV-116
Anderson, M.H.	II-334
Arce-Medina, E.	II-76
Ariman, T.	III-290
Armstrong, J.A.	IV-188, IV-252
Bakke, E.	I-236
Balfour, W.D.	III-119
Bamberger, J.A.	III-398
Bergmann, L.	I-323
Berlant, M.J.	II-218
Bernstein, S.	II-405
Beutner, H.P.	III-71, III-228
Bickelhaupt, R.E.	I-165
Boericke, R.R.	III-353
Bohn, R.	IV-344
Borenstein, M.	III-90
Brookman, E.T.	IV-125
Bump, R.L.	II-425
Bush, P.V.	I-157
Calvert, S.	III-1, III-10, IV-156
Carnes, D.	IV-135
Carr, R.C.	I-118
Chamberlain, H.L.	IV-406

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Chambers, R.	I-45
Chiang, T.	III-250, III-261
Chou, K.H.	IV-73
Cowen, S.J.	IV-264
Crippen, L.K.	I-148
Crowson, F.	III-438
Crynack, R.R.	II-242
Czuchra, P.A.	IV-55
Dalmon, J.	II-390
Demski, R.J.	I-341
Dennis, R.	I-1, III-140
Dietz, P.W.	III-449, III-459
Donovan, R.P.	I-11
Drehmel, D.C.	III-341, IV-210
DuBard, J.L.	IV-383
Durham, M.	II-54, IV-285
Ensor, D.S.	I-176, IV-242
Eskinazi, D.	III-238
Faulkner, M.G.	II-199, IV-395
Feldman, P.L.	IV-3
Ferrigan III, J.J.	I-197
Finney, W.C.	II-358
Fjeld, R.A.	II-179
Fortune, O.F.	I-82

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Frazier, W.F.	III-171
Gardner, R.P.	III-128
Gaunt, R.H.	I-216
Gehri, D.C.	I-333
Gentry, J.W.	III-406
Giles, W.B.	III-468
Hardison, L.C.	III-33
Harmon, D.L.	IV-317
Hawks, R.L.	III-221
Helfritch, D.	I-75
Henry, F.	III-301
Henry, R.F.	IV-63
Hesketh, H.E.	IV-222
Hoenig, S.A.	III-382
Hovis, L.S.	I-23
Hyde, R.C.	I-129
Iionya, K.	III-181, III-321
Jaworowski, R.J.	I-185
Jensen, R.M.	I-138
Joergensen, H.J.	II-370
Johnson, C.A.	I-352
Kalinowski, T.W.	III-311
Kanaoka, C.	III-280
Kirstein, B.E.	III-373

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Kolnsberg, H.J.	IV-179
Krishnamurthy, N.	IV-232
Ladd, K.	I-55, I-65
Lagarias, J.S.	I-272
Landham, Jr., E.C.	I-237
Langan, W.T.	III-211
Lawless, P.A.	II-25, II-35, II-44
Leith, D.	III-270
Leonard, G.L.	II-120
Maartmann, S.	II-130
Mahoney, D.F.	I-206
Mappes, T.E.	III-150
Martin, D.	IV-145
Masuda, S.	II-189, II-380
Mathai, C.V.	IV-200
Mazumder, M.K.	II-160, II-169
McCrillis, R.C.	IV-306
McElroy, M.W.	I-94
McLean, K.J.	I-265, II-304
Menegozzi, L.	II-404
Menoher, C.	III-111
Mitchner, M.	II-97
Moore, W.E.	IV-105
Mormile, D.	IV-363

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Moslehi, G.B.	II-109
Mosley, R.B.	II-1, II-13
Musgrove, J.G.	III-193, III-201
Noonan, F.M.	IV-326
Oglesby, H.S.	III-80
Ostop, R.L.	I-107
Parker, R.	III-51, IV-2
Parquet, D.	III-363
Parsons, Jr., E.L.	I-303
Patton, J.D.	III-160
Pearson, G.L.	I-120
Pedersen, G.C.	III-60
Petersen, H.H.	I-291
Piulle, W.	I-253
Potokar, R.W.	III-417
Prem, A.	III-21
Presser, A.M.	IV-26
Pyle, B.E.	II-66
Raemhild, G.A.	II-349
Reardon, F.X.	III-102
Rimberg, D.B.	II-262
Rinaldi, G.M.	IV-95
Rinard, G.	II-283, II-295
Rubow, L.N.	IV-83

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Rugg, D.	II-273
Samuel, E.A.	II-149
Schliesser, S.P.	II-252
Semrau, K.T.	III-43
Shilling, N.Z.	II-230
Smith, W.B.	I-96
Snaddon, R.W.L.	IV-74
Sparks, L.E.	II-314, II-326
Spawn, P.D.	IV-335
Starke, J.	III-428
Stevens, N.J.	I-313
Sullivan, K.M.	II-141
Tatsch, C.E.	IV-353
Teller, A.J.	III-393
Thompson, C.R.	II-415
Urone, P.	IV-275
VanOsdell, D.W.	I-35
Viner, A.S.	IV-168
Wakabayashi, A.	III-332
Wang, H.H.	IV-36
Wang, J.C.F.	IV-373
Wegrzyn, J.	IV-46
Weyers, L.L.	I-226
Wilks, W.H.	IV-15

AUTHOR INDEX (cont.)

AUTHOR NAME	PAGE
Williamson, A.D.	IV-297
Yamamoto, T.	II-87
Yung, S.	IV-1, IV-155
Zarfoss, J.R.	II-208

☆USGPO: 1982 — 559-092/0429

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Fees Paid
Environmental
Protection
Agency
EPA-335

Official Business
Penalty for Private Use, $300

Special Fourth-Class Rate
Book

Please make all necessary changes on the above label, detach or copy, and return to the address in the upper left-hand corner

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner

EPA-600/9-82-005a

B105
9